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YSSP Report
Young Scientists Summer Program

International socio-environmental spillover effects on achieving the national SDGs

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Approved by

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Program: ASA/BNR
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Abstract

In an increasingly interconnected world, one country's ability to achieve the United Nations Sustainable Development Goals (SDGs) is affected by positive or negative spillovers from other countries. Yet, little research has considered these spillovers in monitoring SDG progress. Ignoring these effects may result in achieving one country's SDGs at the cost of the other or miss positive synergies. To fill the gap, we integrated a global supply-chain database with several international flow datasets, and quantified the impacts of multiple social and environmental spillovers on all the 17 SDGs for 189 countries. Our analysis shows that, globally, international activities (e.g., trade) could help improve the national SDG Index by 20.2%. At the country level, 91% of the countries (accounting for 94% world population) improved their SDG Index through international interactions. Despite the overall benefit, we found that, among the 17 SDGs, 15 benefited from international interactions while two were negatively impacted, and both deal with the dimension of social fairness. Besides, we found higher-income countries generally benefited more, while lower-income countries benefited less and occasionally disadvantaged from the spillover impacts. Further analysis found that the negative spillovers were dominantly generated by a few powerful and developed countries, such as the United States, Germany, Japan, Italy, and China, while the impacted countries are mostly less-developed. Furthermore, we found the spillover impacts more frequently occurred between faraway countries with unequal economic levels, which indicates distant interactions lead to more socio-environmental inequality among countries in terms of achieving SDGs. The study provides a quantitative understanding of the often-ignored spillover effects on achieving sustainability, therefore, inform (inter)governmental agencies to target the negative spillovers and empower disadvantaged countries to better achieve SDGs globally.

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Introduction

Many global challenges are transboundary and entwined to affect the progress towards the Sustainable Development Goals (SDGs) (Liu 2018, Xu et al 2020, Sachs et al 2021). However, SDG assessments have been largely focusing on evaluating the progress within country boundaries at national and global scales (Sachs et al. 2019; Xu et al. 2020a), knowledge about the transboundary impacts on goal achieving is still lacking. Transnational flows of goods, services, capital, information, and people increased dramatically in the last decades, underpinning a world that is more interconnected than ever, with increasing socioeconomic and environmental interactions between adjacent systems ("pericouplings"), as well as between distant systems ("telecouplings"), in addition to the conventional focus of interactions within a system ("introcouplings") (Liu et al 2015, 2018). As a consequence, one country's policies or actions can have expected and unexpected transnational spillovers on other countries' efforts to achieve the goals. For example, studies have revealed that developed countries tend to transfer energy- and carbon-intensive industries to less developed countries, which hinders the progress towards goals such as climate and sustainable industries in those less developed countries (Xu et al. 2020b; Sachs et al. 2021). In addition to the prominent environmental spillovers such as carbon leakage (Feng et al. 2013) and biodiversity loss (Lenzen et al 2012), recent studies have called for extended attention to the often ignored spillovers in the social dimension (e.g., vulnerable employment, child labor, and health risks) (Alsamawi et al. 2017, Xiao et al 2017, Simas et al 2014, Chung et al 2021) and the economic dimension (Malik et al 2021). With the frequency and intensity of transboundary interactions (e.g., trade) increasing between countries (Tromboni et al. 2021), it is urgent to know the extent to which these transnational spillovers shaped the national progress towards the 17 SDGs. Ignoring these spillovers may result in achieving one country's SDGs at the cost of the other, or miss opportunities for synergistic co-actions.

Existing studies have attempted to use a spillover index, consisting of a few indicators, to measure the external impacts one country may generate (Schmidt-Traub et al. 2017; Sachs et al. 2020, 2021; Zeng et al. 2021), but did not explicitly reveal the extent of impact on SDG progress. With a recent study revealing that international trade impacts nine environment-related SDG targets (Xu et al. 2020b), it is also pressing to know how international trade impacts a broader spectrum of goals and targets (e.g., in environmental, social, economic, and national security dimensions), as well as to know how other types of spillovers through international interactions besides international trade may impact SDGs. Furthermore, most of these studies only examined the aggregated spillover impact of one country on the rest of the world (Xu et al. 2020b; Sachs et al. 2021), while the information on how each country-pair impacts on each other is still missing. Such information is urgently needed for (inter)governmental agencies to target these unexpected international impacts, and minimize their negative impacts while enhancing the positive ones to achieve all SDGs globally. It is particularly important to identify such gaps now as the world is at the critical beginning stage of the UN Decade of Action to achieve its Sustainable Development Goals by 2030 for all.

Here, we report the first global analysis of the dynamic impacts of a range of spillovers (e.g., socio-environmental impacts embodied in international trade) on achieving national SDGs. Specifically, we address: (1) Which SDGs are most affected at the global scale, and to what extent? (2) Do the impacts vary across economic development levels and locations? (3) Which countries made the most impacts, and which were most impacted by the spillovers? To address these questions, we compiled data and indicators on all 17 SDGs (with 45 indicators, listed in Supplementary Table 1) for 189 countries for the nominal year 2015. We included the measurable SDG indicators and those that are directly influenced by at least one of the 43 transnational impacts (measured by footprint indicators, listed in Supplementary Table 2; see Methods). To quantitatively measure the impacts, we estimated how a country's SDG performance would change when the world changed from the current globally metacoupled system (the baseline) to a hypothetical global lock-down scenario (i.e., no transnational interactions among countries but only domestic activities, e.g., no international trade; the consequence caused by the recent COVID-19 global pandemic is the best approximation of this scenario; see Methods). We first measured the transnational impacts on each SDG, and then calculated the aggregated impacts on the SDG Index score of each country. Here, SDG Index is the aggregated score of the 17 SDGs for characterizing countries' overall SDG performance (see Methods). We further compared the difference in the extent to which the impacts on SDGs vary across countries, and income groups, as well as the difference in adjacent and distant interactions. This measurement can help test if telecoupling impacts—generated from distant interactions—are more prominent than adjacent ones in affecting a nation's progress towards achieving SDGs. Finally, we apply network analysis to identify key actors and characterize their interactions over time in the global interactive networks. This research is the first to integrate environmental-, social-, economic-, and security-related spillovers to investigate multifaceted transnational effects on SDGs by applying the metacoupling framework (socio-economic–environmental interactions within as well as between adjacent and distant places (Liu 2017)). The findings can help identify the complex mechanism behind goal-achieving efforts, and improve the equality of intergovernmental conventions for achieving SDGs globally.

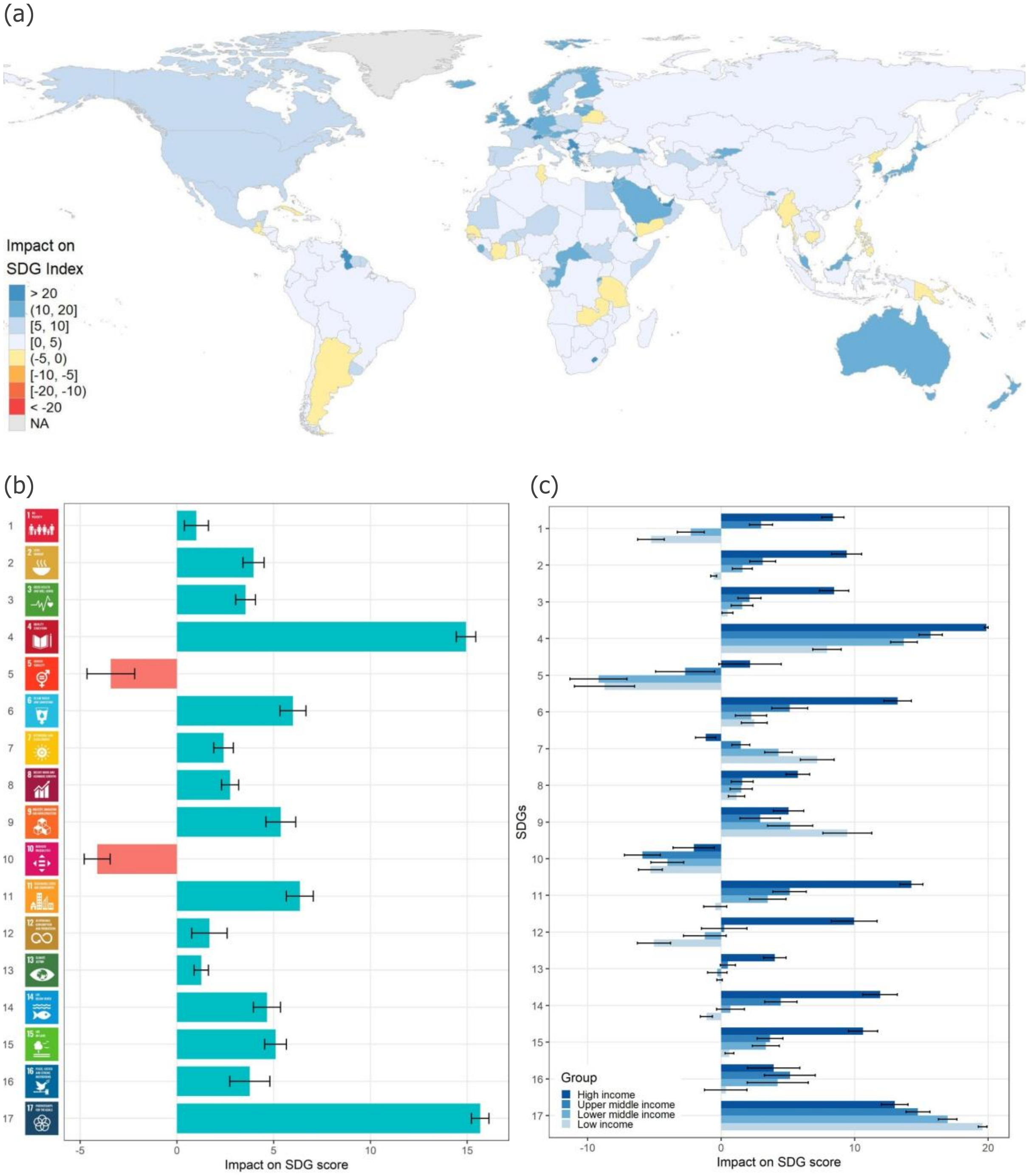
Results

The overall impact of spillovers on SDGs

Comparing the two scenarios, globally, the SDG Index of countries increased 20.2% (or 8.1 scores) on average (mean = 66.2, s.d. = 9.9, with scoring on a scale of 0 - 100) from international spillovers. At the country level, 91% of the 189 countries (accounting for 94% world population) improved their SDG Index from global interactions. Only 9% of the countries (n = 13) decreased their SDG Index, over three-quarters of which are lower-income countries (Fig. 1a, Extended Data Fig. 1).

Among the 17 SDGs, 15 benefited from international spillovers (Fig. 1b), with SDG 17 (Partnerships for the Goals) and SDG 4 (Quality Education) improved most, followed by SDG 11 (Sustainable Cities and Communities), SDG 6 (Clean Water and Sanitation), SDG 9 (Industry, Innovation and Infrastructure), and others. However, two SDGs (SDG 5 - Gender Equality, and SDG 10 - Reduce Inequality) were negatively impacted and both deal with the dimension of fairness.

The impact on the nation's SDGs also varied across income groups (Fig. 1c). We found higher-income countries generally benefited more (on 14 of the 17 SDGs), while lower-income countries benefited less and occasionally even lowered scores from spillovers. In addition, although most countries improved their SDG Index, aggregated from all 17 Goals, not all Goals of a nation gained positive impacts. Countries in the Global South saw their SDG Index score lowered in more than one-half of their 17 goals, particularly countries in Africa and South Asia (Fig. 1d). While countries in the Global North gained scores in more than half of their 17 goals, European countries and the US benefited in more than 80% of the 17 goals.


(a)
Impact on
SDG Index
> 20
(10, 20]
[5, 10]
[0, 5)
(-5, 0)
[-10, -5]
[-20, -10)
< -20
NA
(b)
Impact on SDG score
(c)
SDGs
Group
High income
Upper middle income
Lower middle income
Low income
Impact on SDG score

(d)

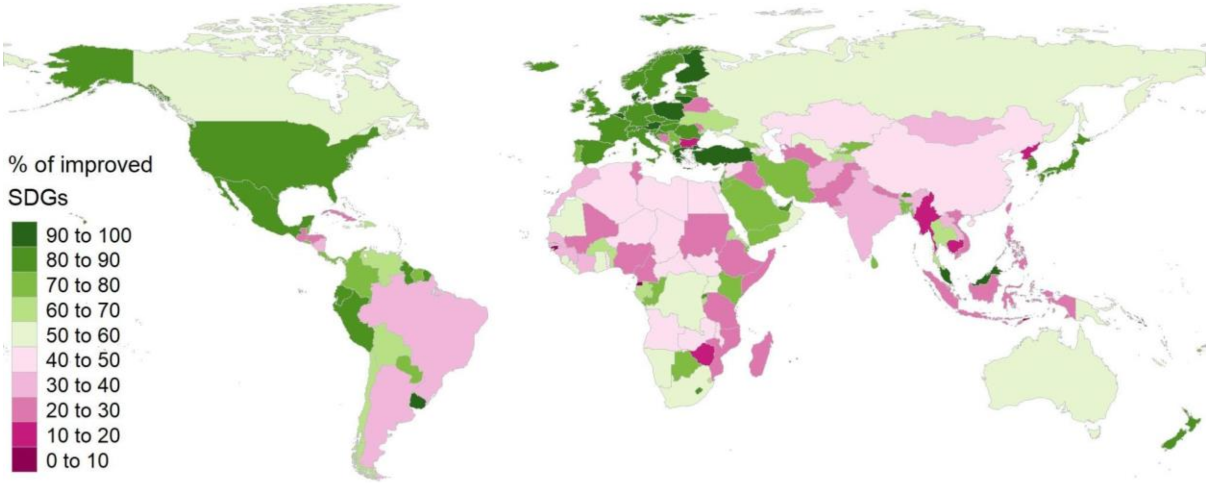


Fig. 1. The overall spillover impact on SDG Index and individual SDG score at the global scale.
(a) The overall impacts on each country's SDG Index (i.e., aggregated SDG scores). Positive values mean one country's SDG score benefited from spillovers. (b) The overall impacts on each Goal of the 189 countries. The error bars indicate the standard errors in the SDG scores across countries (n = 189). (c) The overall impact on each Goal by country income group. The income group categories are based on the World Bank's classification. The error bars indicate the standard errors in the SDG scores across countries in each income group. (d) Percent of improved SDGs from spillovers. SDG Icon images courtesy of the United Nations.

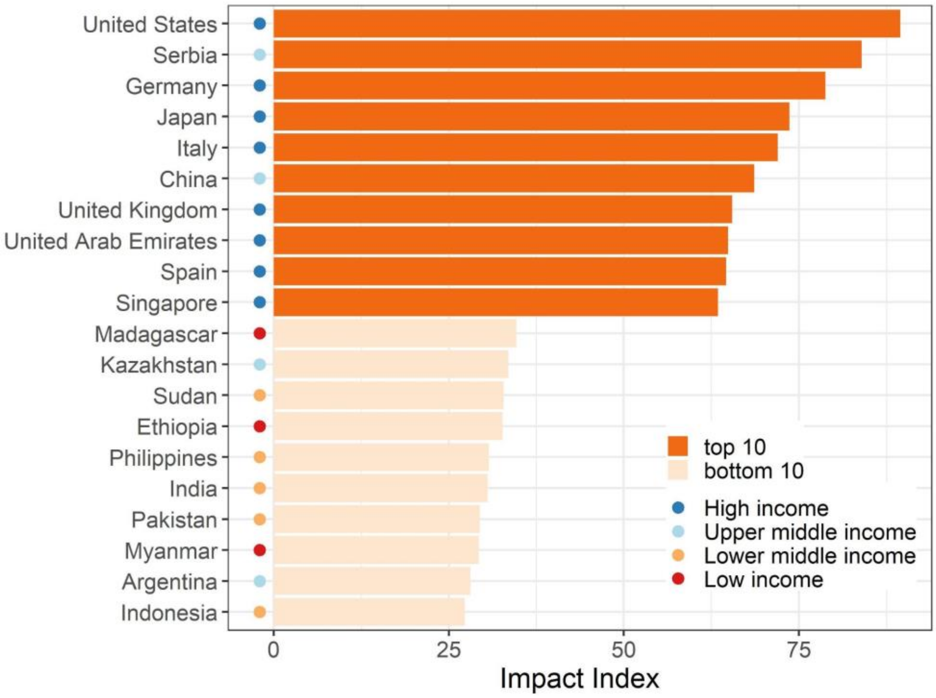
Dominate actors in the global spillovers networks

Ranked by the aggregated spillovers (based on 43 spillover indicators), the top 10 countries that made the most negative impacts through spillover effects on the rest of the world are the United States, Serbia, Germany, Japan, Italy, China, United Kingdom, UAE, Spain, and Singapore (Fig. 2a, 2b). While the bottom 10 countries, including Indonesia, Argentina, Myanmar, Pakistan, India, Philippines, Ethiopia, Sudan, Kazakhstan, and Madagascar, are those that made the least negative impacts. Interestingly, we found all of the top 10 influencers are in the higher-income country group, while almost all of the bottom 10 are lower-income countries. Noteworthily, countries' social spillover impacts on SDGs can be surprisingly as large as (or even larger than) environmental spillovers, which was not reported in existing literature (Extended Data Fig. 2).

When zooming into the complex spillovers network, we noticed that most of the distant responsibilities of impact point to the top influencers (Fig. 2c). For example, the USA, Serbia, Japan, and China are the countries most responsible for their transnational impacts. Similarly, India, Indonesia, and Argentina are most affected in the simplified core network (Fig. 2c, Supplementary Fig. 1).

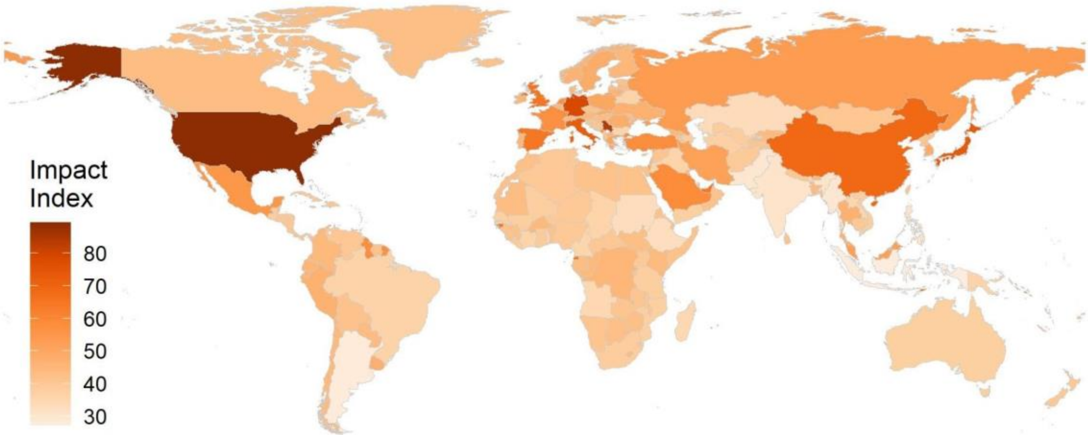
Not only do more developed countries tend to impact less developed countries through spillovers, but also we found the impacts were more frequently generated between faraway countries with unequal economic levels (Fig. 2d). That is, telecouplings lead to more socio-environmental inequality among countries in terms of achieving the UN's SDGs.

(a)



United States
Serbia
Germany
Japan
Italy
China
United Kingdom
United Arab Emirates
Spain
Singapore
Madagascar
Kazakhstan
Sudan
Ethiopia
Philippines
India
Pakistan
Myanmar
Argentina
Indonesia
top 10
bottom 10
High income
Upper middle income
Lower middle income
Low income
0
25
50
75
Impact Index

(b)



Impact Index
80
70
60
50
40
30

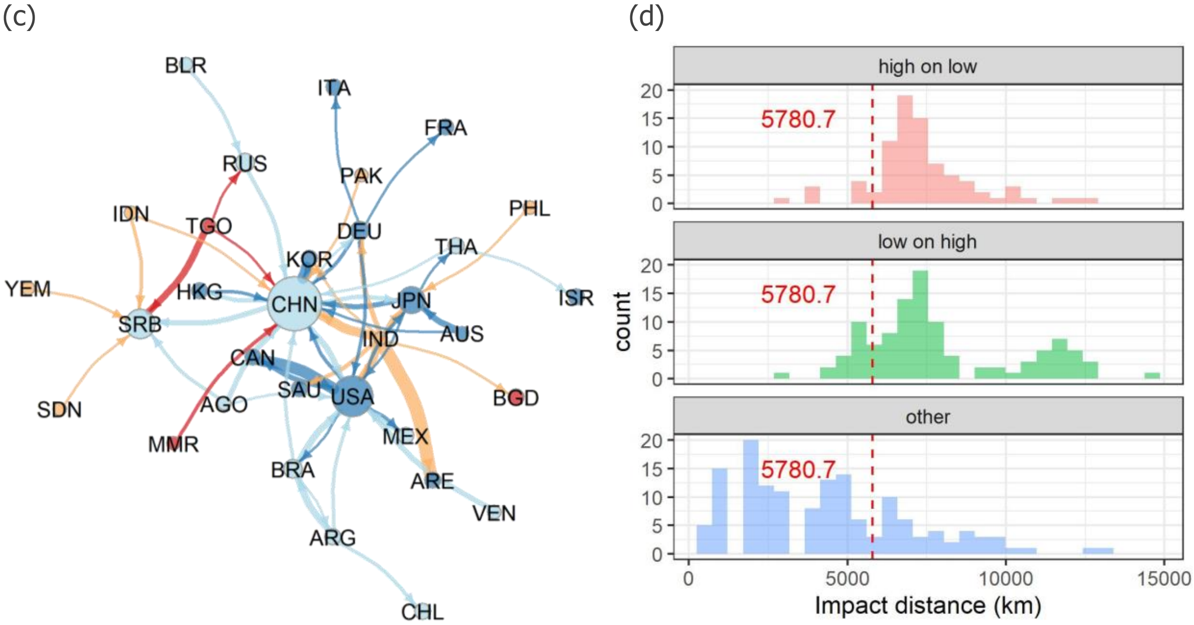


Fig. 2. Dominant influencer and affected in the global spillovers network.
(a) Top 10 and bottom 10 influencers of the 189 countries in 2015, ranked by spillover index (i.e., aggregated impact scores). High values mean larger negative impacts on the rest of the world. (b) Map of spillover index by country. (c) Network of the top 15 metacoupled country pairs. The arrows point to the dominant influencers (or responsibility takers); The width of edges represents the magnitude of impact. (d) Distribution of the average impact distance between different country-pairs ("high" represents high-income countries, "low" represents lower-income countries, while "others" stands for all other mixed combinations). The red dash line indicates the average impact distance among all possible country pairs.

Discussion

This study presents the first quantitative assessment of the impacts of multiple spillovers (e.g., international trade, financials) on progress toward achieving the 17 SDGs. Our approach advanced previous research by synthesizing the most comprehensive footprint indicators, including both environmental and social aspects to uncover the transboundary impacts on the global and national SDGs. Overall, our results indicated that the international spillovers could help increase the national SDG Index by around 20%. However, with the cutdown of critical supply chains (265 million people are likely to face acute food shortages), international development aid (could drop by US$25 billion in 2021), and international tourism (could drop by 60%) because of global lockdown (Naidoo and Fisher 2020; Verschuur et al. 2021), many SDGs were greatly impacted. Research has warned that two-thirds of the goals are unlikely to be met due to the COVID-19 pandemic (Naidoo and Fisher 2020). For post-pandemic recovery, it is especially urgent to rebuild the global connections and partnerships to keep countries on track towards the SDGs.

Despite the overall benefit of international interaction to help achieve SDGs, we also found that, for individual goals, the spillovers helped elevate 15 out of 17 SDGs, but undermined two SDGs on achieving "equality". This finding is consistent with previous research that revealed international trade improved seven environment-related SDGs at the global level (Xu et al. 2020b), but further revealed international interactions (including trade) improved the other eight SDGs. Besides, we found two SDGs (SDG 5 and SDG 10), which were not covered in previous research, were negatively impacted. This demonstrated that to have a holistic understanding of the transnational impacts on SDGs, it is important to take a wide range of transnational environmental and social interactions into consideration and cover all the 17 SDGs.

The difference in impacts also is reflected in another important finding that higher-income countries generally benefited more while lower-income countries benefited less or even lost scores from international spillovers. As existing literature suggests, developed countries usually gain environmental benefits at the cost of developing countries (Sachs et al. 2020; Xu et al. 2020b), and developing countries often bear most of the environmental burdens, such as resource depletion (Dalin et al. 2017), environmental degradation (Oita et al. 2016) and biodiversity loss (Lenzen et al. 2012). The inequality in environmental impacts is often embodied in international trade and global supply chains. Many have urged to initiate a World Environment Organization (WEO) (Biermann 2020) because international free trade supported by the World Trade Organization (WTO) disproportionately emphasizes more on achieving maximization of economic benefit while much less on the environment. Although existing multilateral and bilateral environmental agreements, such as CITES, UNFCCC, and IPCC have achieved a great deal and reduced the speed of environmental degradation, there still are several pressing environmental problems prevailing throughout the world because many of the multilateral environmental agreements are regional in scope, some are conflicting with each other (Kim and Bosselmann 2013; Kanie 2018; Azizi et al. 2019). In addition to the environmental impacts, transnational social impacts such as corruption (Xiao et al. 2018), labor-related human rights (Alsamawi et al. 2017), education, and gender inequality are also prominent but were much under-reported. While we found the overall transnational social impacts on a nation's SDGs are usually as large as the environmental ones, and can be even larger in some countries (Extended Data Fig. 2). Future policy integration for sustainable development through multilateral environmental agreements needs to better integrate environmental concerns with social and economic issues. Policy conversations and coordination at the global level should also better empower less developed countries towards sustainability because stringent regulations in developed countries can lead to leakages of pollution-intensive and high-social-risk industries to less-developed countries with lax regulations (Shapiro 2020). A recent UN ban on plastic exports has been in effect in the European Union (Adyel 2021), and this action will help countries in the global south to bear less environmental and health-related burdens that are embedded in the low-quality or difficult-to-recycle wastes. Other ways to empower less developed countries include promoting global green financing (Galaz et al 2018, Belhabib and Le Billon 2018) and knowledge/ technology transfer.

The SDGs are global in scope and emphasize to ensure no one is left behind. However, our analysis found the current world, being an intercoupled socio-environmental system, is dominated by a few powerful and affluent countries, such as the United States, Germany, Japan, Italy, and China. Most of the negative spillovers they exert on other countries are through their high footprints in international trade, which is often structured in asymmetrical power relationships (e.g., in terms of affluence and military) between countries that give extra advantages to the more powerful nations and can sometimes be quite disadvantageous to the less powerful (Jorgenson 2016). In addition, our analysis found transnational impacts more commonly happening between faraway countries with unequal economic levels. Perhaps adjacent countries have more similar socio-economic and environmental conditions that determine the categories of resources and services for exchange, while distant exchanges can diversify the supplies (Xu et al. 2020b). Furthermore, the spatial segregation of countries by affluence levels (i.e., higher-income countries are mostly located in the Global North, while lower-income countries are in the Global South, see Supplementary Fig. 2) also make "telecouplings" more prominent. Environmental sociologists have conducted extensive case studies on ecological footprint and carbon emissions and confirmed the increasingly ecological unequal exchanges between developed countries and less-developed countries (Jorgenson 2012, 2016). With our finding that unequal exchanges are prominent both environmentally and socially, future environmental justice and structural inequality scholars may also need to examine these aspects to provide more in-depth insights for international policy-making.

Our analysis on mapping the transnational social and environmental impacts on 17 SDGs for each nation pair can help nations identify which countries impact their sustainability efforts and on which aspects. Such information will be useful for maximizing the positive impacts and minimizing the negative impacts to better achieve the SDGs. Due to the inherent complexity in the globally intercoupled networks, we estimated the transboundary impacts on SDGs by comparing the SDG scores under the current intercoupled world (the baseline) to a counterfactual global lock-down scenario. Although this approach has been widely used in trade-scenario settings (Wood et al. 2018; Xu et al. 2020b) and was previously thought to be unlikely to happen, the recent global lockdown caused by the COVID-19 pandemic provided a factual case. Nevertheless, future research on better estimating and predicting the transboundary impacts on SDGs can adopt multiple scenarios and use more sophisticated models (e.g., the Global Biosphere Management Model -- GLOBIOM) (Havlík et al. 2018). This research also lays a foundation for further exploring the transboundary impacts on sustainable development at finer scales, such as at the sub-national level, corporation level (Malik et al. 2021), and even pixel level by integrating satellite earth observation with supply chain data (Moran et al. 2020; Burke et al. 2021). With richer data available to fill the current data gaps in evaluating SDG progress, scientists would be able to have a better understanding of the complexity in the transboundary impacts. Further facilitating global partnerships, public-private partnerships (Lambin and Thorlakson 2018) and multi-stakeholder initiatives (Pattberg and Widerberg 2016; Sachs et al. 2019) can be effective ways to achieve the SDGs for all.

Methods

SDG Indicators and SDG Index

We collected data for 189 countries on 45 indicators (Supplementary Table 1) that operationalized the 17 SDGs in the nominal year of 2015 using the best data available. These indicators were drawn primarily from the UN's "Global indicator framework for the Sustainable Development Goals and targets of the 2030 Agenda for Sustainable Development" (UN 2019). Besides, we also considered indicators used in the Sustainable Development Reports (Sachs et al. 2020) and the UN's report on "Indicators and a Monitoring Framework for the Sustainable Development Goals" (Schmidt-Traub et al 2015). These reports were published by the Sustainable Development Solutions Network (SDSN), which operates under the auspices of the UN to promote the implementation of the SDGs and the Paris Climate Agreement. In addition, we also included SDG indicators that are used in existing literature (Xu et al. 2020a, b; Sachs et al. 2020, 2021) to cover as many SDG targets and goals as possible within the constraints of data availability across countries for the study period. Data were mainly obtained from the FAO (Food and Agriculture Organization of the United Nations), the World Bank, the ILOSTAT (International Labour Organization Database), EDGAR (the Electronic Data Gathering, Analysis, and Retrieval system), and other sources (See details in Supplementary Table 1). We selected and included these 45 SDG indicators because they are measurable and are directly influenced by at least one of the 43 transnational impacts (measured by footprint indicators, listed in Supplementary Table 2). This might underestimate the transnational impacts on SDGs when left out indicators that are either not measurable or have less attributable (or indirect) linkages with spillovers at this moment. Nevertheless, this study provides by far the most comprehensive evaluation of the spillovers on SDGs.

To make the evaluation comparable across countries and across time, we follow SDSN and Xu et al.'s approach (Xu et al. 2020a; Sachs et al. 2021) and normalized all SDG indicators to values ranging from 0 (indicating the worst performance) to 100 (indicating the best performance). "Performance" refers to one country's progress toward achieving the SDGs. We further used an SDG Index score (0-100) consisting of individual normalized SDG scores (0-100) for characterizing countries' overall SDG performance. SDG Index score is an aggregate score composed of individual scores of the 17 SDGs, representing each country's overall performance in achieving all 17 SDGs (Sachs et al 2019). We calculated each country's SDG Index score by using an equal-weight average approach, with the emphasis that the UN takes integrated solutions to address all 17 SDGs equally (Sachs et al 2019). Within each goal, all indicators are also equally weighted. Therefore, theoretically, the SDG index could range from 0 to 1700, while we found a range of SDG Index between 0-100 is more intuitive for readers and stakeholders to know the gap from fully (100%) achieving the goals. For example, a country with a score of 50 indicates halfway towards achieving the best performance.

Linking Transnational Spillover Impacts with National SDG Performance

In an increasingly intercoupled world, one country's sustainability initiatives and actions can generate positive or negative transnational impacts on other countries, and sometimes in turn impact on itself. Taking soybean trade as an example, research found importing soybean to enhance food security not only causes deforestation in exporting countries but also environmental pollution in importing countries (Sun et al. 2018). Besides the commonly reported transnational environmental impacts (Dalin et al. 2017, Oita et al. 2016, Lenzen et al. 2012), there are also considerable social impacts embodied in international interactions (Wiedmann and Lenzen 2018, Dorninger et al. 2021). Furthermore, in addition to international trade, other types of international interactions are understudied. For example, international development finances also play a big role (Galaz et al. 2018; Turner 2019), as achieving the SDGs requires mobilizing resources from a variety of sources, including international partners, domestic budgets, foundations, and philanthropy, as well as the private sector. It is estimated that achieving the Sustainable Development Goals by 2030 will require a rough estimate of US$5-7 trillion dollars (5.8% ~ 8.3% of global GDP) of annual investment across sectors and industries (UN 2018). To comprehensively characterize the international impacts on achieving sustainable development, it is necessary to take a system perspective and investigate the multiple facet impacts of one transnational activity.

We thus synthesized indicators from the literature, and grouped different transnational spillover impacts into four broad categories (Sachs et al. 2020): (1) Environmental spillovers, (2) Social and governance spillovers, (3) Economy and finance spillovers, and (4) Security spillovers. Here, we matched these spillovers with specific SDG indicators to estimate the extent to which one country may affect other countries' SDG progress or be affected by spillovers from other countries. We compiled global datasets and indicators and utilized models (see detailed description in the following) on measuring a list of 43 spillovers (see Supplementary Table 2) for 189 countries.

Environmental spillovers

Environmental spillovers cover spillovers related to the use of natural resources and pollution. Environmental spillovers can be generated in two ways: 1) through transboundary environmental impacts embodied in trade, and 2) through direct cross-border flows in air and water (Sachs et al. 2020). In this study, we focus on international trade-related environmental spillovers, because the quantification approaches such as multi-region input-output (MRIO) analysis have been full-fledged and been applied to measure a range of transboundary environmental impacts (e.g., land use, water scarcity, energy use, carbon emissions, nitrogen emissions, and biodiversity) embodied in consumption and trade (Lenzen et al. 2012, 2013; Tukker and Dietzenbacher 2013; Oita et al. 2016; Wiedmann and Lenzen 2018; Xu et al. 2020b). However, quantifying cross-border flows through air and water for each country at a global scale remains a great challenge, which we choose not to cover the environmental spillovers generated in this way. Here, we linked the SDG indicators with a new high-resolution global MRIO database, Eora (Lenzen et al. 2011), to calculate environmental spillovers (e.g., land/water/energy use, carbon emissions; see the list in Supplementary Table 2).

Social and governance spillovers
Social and governance spillovers cover international labor standards (e.g., occupational injuries and fatalities), corruption footprints of nations, and other social supply chain impacts (Alsamawi et al. 2014, 2017; Xiao et al. 2017, 2018; Malik et al. 2021). Social impacts are usually challenging to be quantified, especially at the global scale and along the global supply chains. Here, we match MRIO with the novel Social Hot Spots Database (SHDB) (Norris and Norris 2015) to fill the research gap on quantitatively estimating social spillovers (see the list in Supplementary Table 2).

Economy and finance spillovers
Economy and finance spillovers cover international development finance (e.g., official development assistance; ODA), unfair tax competition, and banking secrecy (Sethi et al. 2017; Turner 2019; Sachs et al. 2020). In this study, we used the international development finance data coded by AidData. The AidData provided by far the most comprehensive project-level estimates of contributions of international financials to the SDGs (and their associated targets) using development project descriptions (DiLorenzo et al. 2017). These data and methodology provide information such as where development financing is targeted, from which country, and how much. Researchers at AidData have assigned codes to over 800,000 project descriptions through a double-blind coding methodology, providing more granular data on project activities and purposes. Briefly, this coding methodology involves three critical steps: (1) creating a mapping between activity codes and SDG targets, (2) splitting an aid project across designated financial activities, and (3) splitting activity amounts across SDG targets, as a financial activity may be linked to multiple targets. From these calculations, target-level estimates can be summed up to the goal level. As a financial activity may be linked to multiple targets, the methodology weights a financial activity's contribution to the SDGs proportional to the number of SDG targets that appeared in the mapping between that activity and the targets. For example, if financial activity A is linked to three SDG targets 1.1, 1.2, and 3.1, then 2/3 of financial activity A will be deemed as a contribution to SDG 1 and 1/3 to SDG 3. For a detailed coding process and uncertainty discussion, please refer to (DiLorenzo et al. 2017; Turner and Burgess 2019).

Security spillovers
Security spillovers include negative spillovers – such as the trade-in arms and organized international crime, and positive spillovers – such as investments in conflict prevention and peacekeeping (Wezeman et al. 2018; Sachs et al. 2020; Béraud-Sudreau et al. 2020). We compiled international arms transfers data from Stockholm International Peace Research Institute (SIPRI) Arms Transfers Database, and the Troop and Other Personnel (e.g., police) Contributions data from the UN Peacekeeping Open Data Portal and the SIPRI Multilateral Peace Operations Database. Similar to (Sachs et al. 2020), we used the number of traded arms from country m to country n as an indicator of negative security spillovers, and the number of troops and other personnel (e.g., police) contributions from country m to country n as an indicator of positive security spillovers.

Network Analysis

We use network analysis to reveal the relative importance of each country in impacting other countries' sustainable development. Each node in the network represents a country, and the node size tells us how central the node is in the complex network. We use the "centrality" indicator computed using the igraph package (Csardi and Nepusz 2006) to characterize the node size. The edge linking two country pairs demonstrates an impact relationship. The arrows point to the dominant influencers (or responsibility takers), and the width of edges represents the magnitude of impacts.

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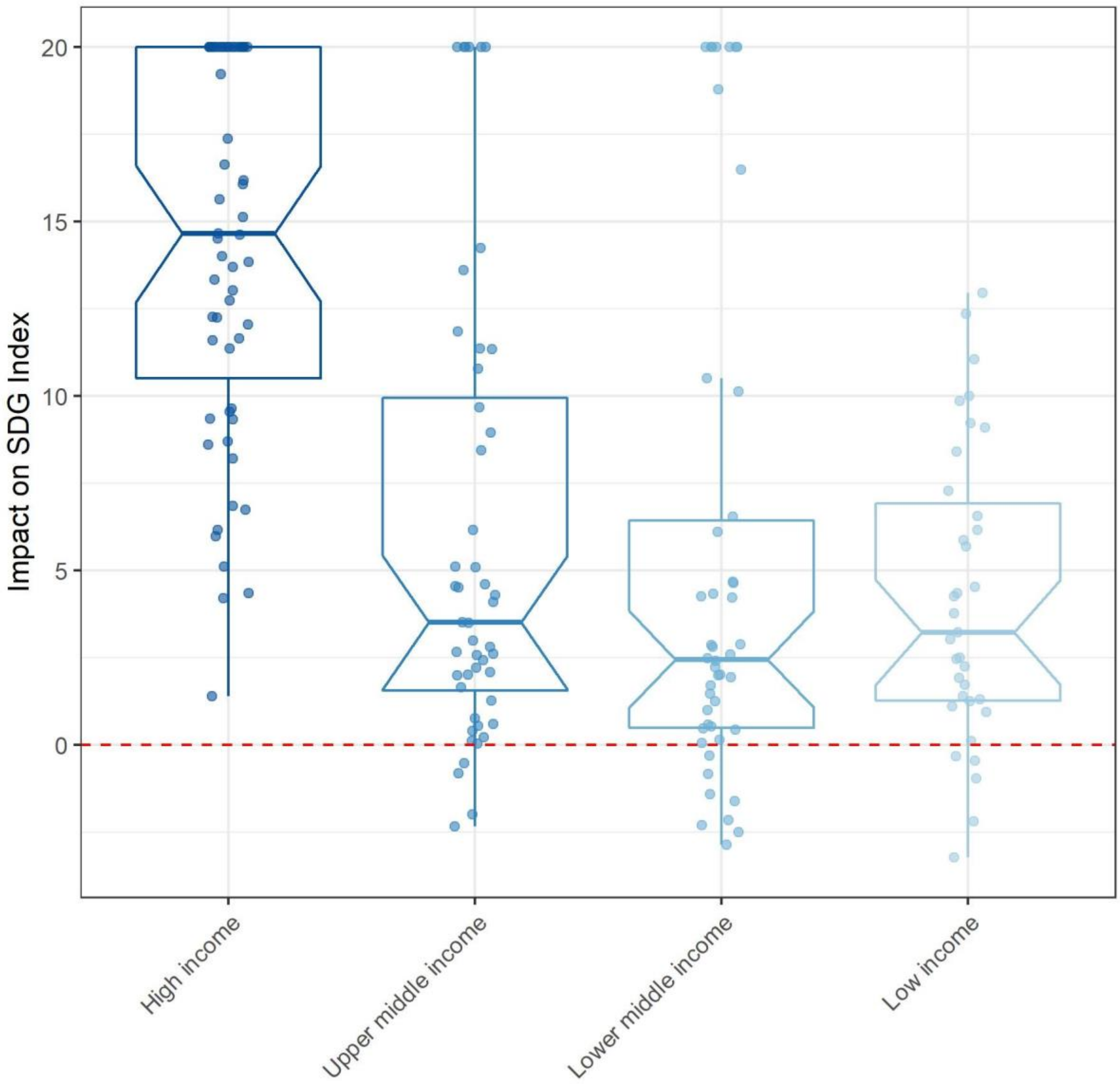
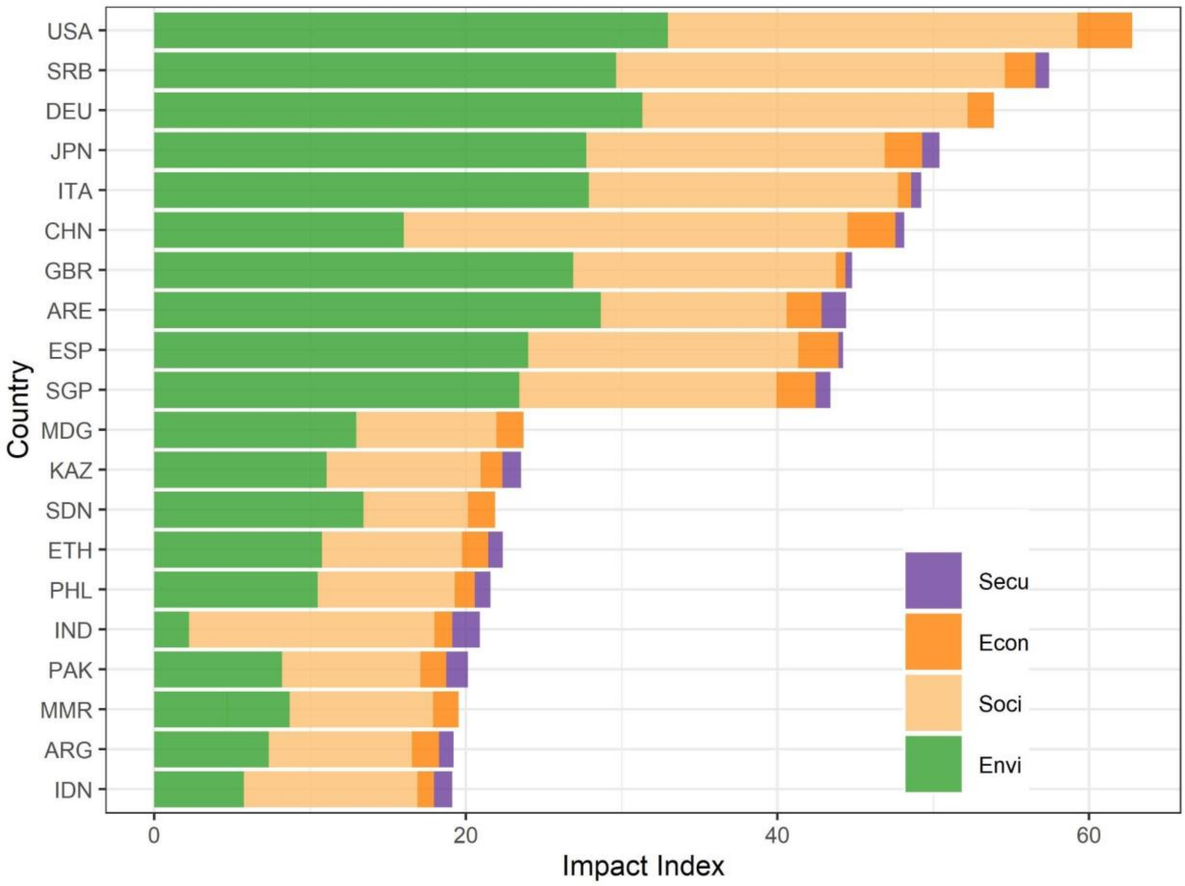
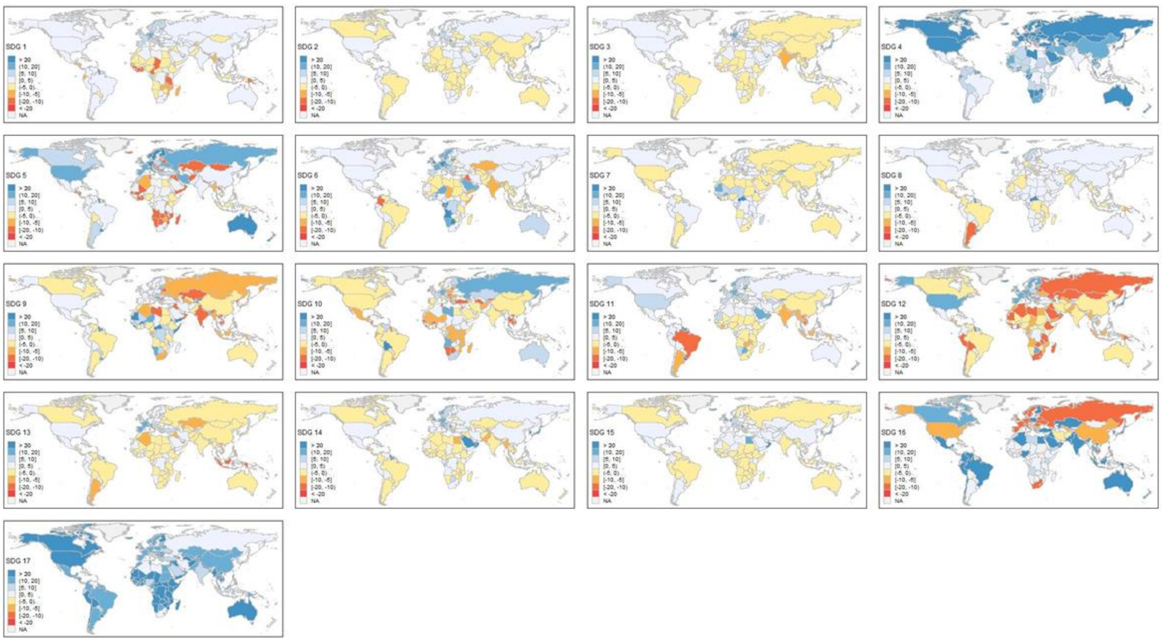


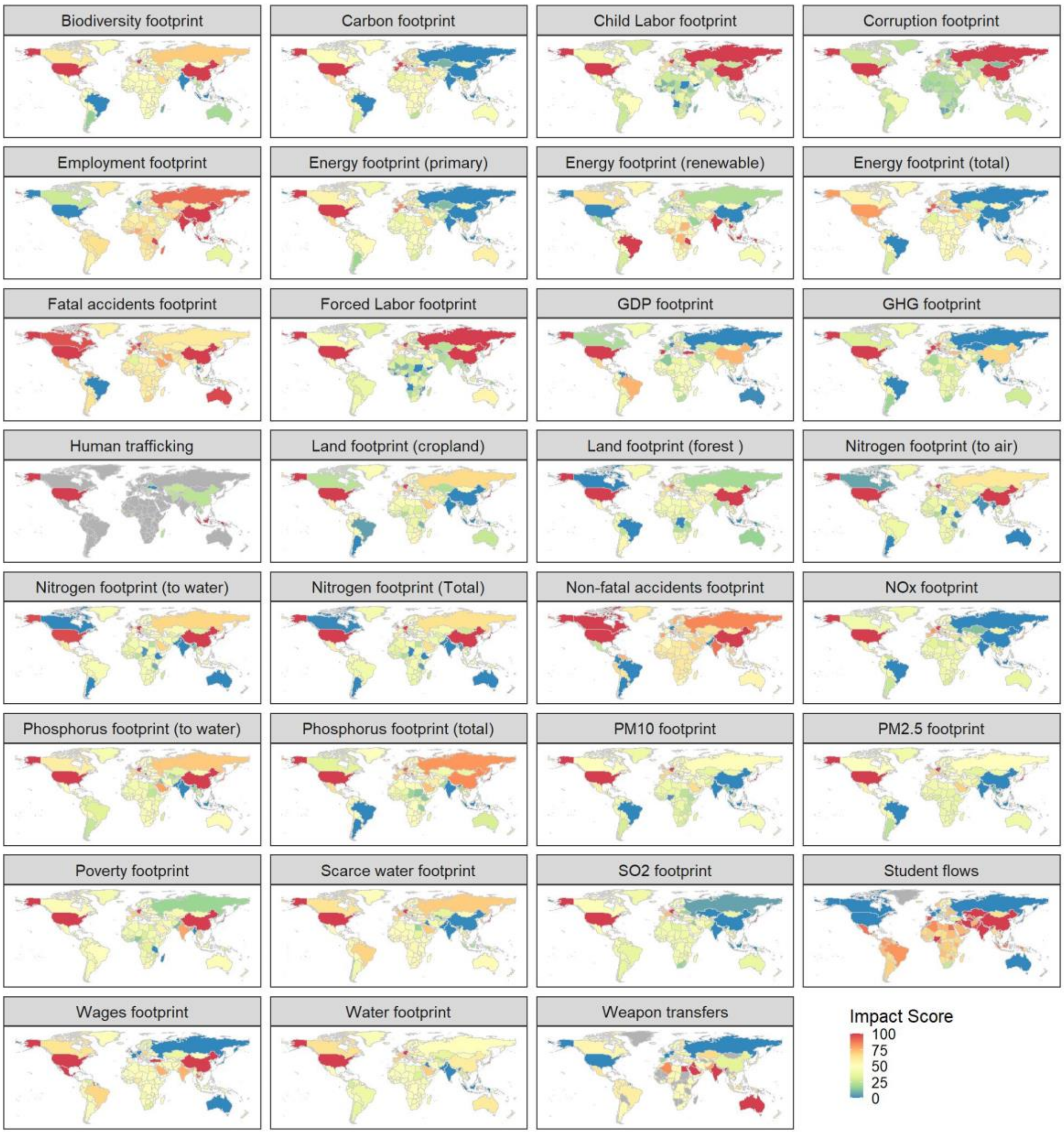
Extended Data Fig. 1. Spillovers on SDG Index by income group.
A value above 0 means a positive impact on a nation's SDG Index, while a value less than 0 indicates a negative impact on a nation's SDG Index. In each boxplot, the central rectangle spans the first quartile Q1 to the third quartile Q3, while the segment inside the rectangle indicates the median. Each dot represents a country.



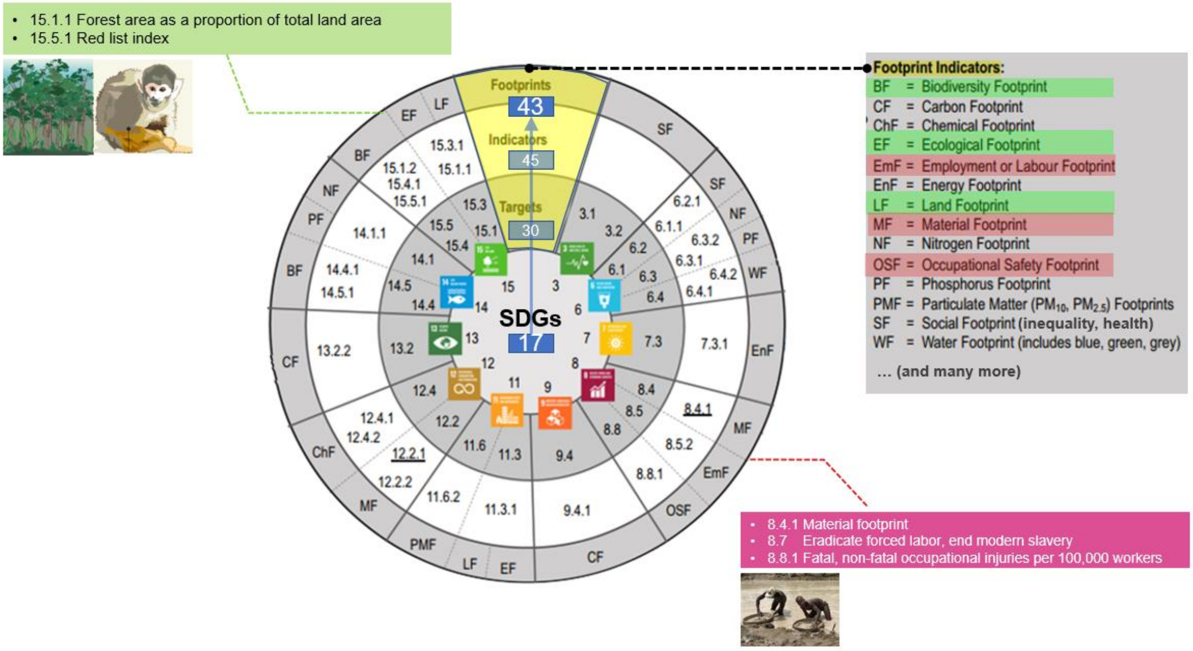
Extended Data Fig. 2. Different types of spillovers by the top 10 and bottom 10 influencers, ranked by spillover index (i.e., aggregated impact scores).
High values mean larger negative impacts on the rest of the world. Full names of the countries are listed in Supplementary Table 3.



Extended Data Fig. 3. Spillover impacts on each SDG at the country level.



Extended Data Fig. 4. Impact of each spillover.
Refer to Supplementary Table 2 for the full name of each spillover.



Extended Data Fig. 5. Demonstration of the linkage between SDGs and spillovers. Shown are the 17 SDGs (center), 30 SDG targets (first ring), and 45 SDG indicators (second ring) that relate to 43 specific transnational footprint indicators (third ring). Five SDG indicators under SDG 8 and SDG 15 are presented in the figure for a demonstration purpose only. A full list of matched linkage between SDGs and spillovers can be found in Supplementary Table 1.

Supplementary Information

Supplementary Methods

MRIO analysis for quantifying spillovers embodied in international trade

We applied multi-regional input-output analysis to quantify spillovers (such as virtual water, CO_2, energy, raw materials, and land) embodied in international trade. This footprint-based measurement can quantify the amount of natural resources required or social risks along the supply chain for the production of goods and services (Zhao et al 2015, Feng et al 2013, Wiedmann et al 2015). For instance, CO_2 emissions are produced during the entire production and supply chain of goods and services.

MRIO has been widely used to study economic interdependencies between countries by tracking monetary flows. Assuming there are m countries and every country has n sectors, the monetary output of sector i in country R can be calculated using the following equation:

$$x_i^R = \sum_{S=1}^{m} \sum_{j=1}^{n} x_{ij}^{RS} + \sum_{S=1}^{m} y_i^{RS} \quad (1)$$

where x_{ij}^{RS} is the value of monetary flows from sector i of country R to sector j of country S, and y_i^{RS} represents country S's final demand that is supported by sector i of country R.

The direct input coefficient a_{ij}^{RS} is derived from equation (2):

$$a_{ij}^{RS} = x_{ij}^{RS} / x_j^S \quad (2)$$

where a_{ij}^{RS} is the value of monetary flows from sector i of country R that contributes to one unit of monetary output in sector j of country S.

If we let *X*=[x_i^R], *A*=[a_{ij}^{RS}] *and Y*=[y_i^{RS}], we can calculate the following matrix *X* based on Eq. (1):

$$X = A \cdot X + Y \quad (3)$$

Then we rearranged and formulated the Eq. (3) as:

$$X = B \cdot Y; \; B = (I - A)^{-1} \quad (4)$$

where $(I - A)^{-1}$ is the Leontief inverse matrix, suggesting both direct and indirect monetary value flow from other countries to meet one unit of final monetary demand.

To calculate the amount of virtual resources and social risks embodied in international trade, we first calculated the direct resource intensity coefficient. The direct resource intensity coefficient of sector i in country R is expressed as:

$$e_i^R = w_i^R / x_i^R \quad (5)$$

where w_i^R is the total resource/material intensity in sector i of country R; therefore e_i^R is the amount of resource/material consumed/emitted to increase one monetary unit of output in sector i in country R.

If we let *E*=[e_i^R], then we can calculate the virtual resource (VR) transfer matrix using the following equation

$$VR = E \cdot B \cdot Y \quad (6)$$

The amounts of virtual water, energy, material, CO_2, and social risks embodied in yearly trade for each country/region therefore are calculated. A more detailed description about global virtual resource flows can be found in our earlier publication (Xu et al 2020).

Supplementary Table 1. SDG indicators that impacted by international spillovers

SDG	SDG Indicator	Spillover indicators	References
1	1.1.1 Proportion of the population living below the international poverty line	Poverty footprint	by Authors
2	2.4.1 Proportion of agricultural area under productive and sustainable agriculture	Land footprint (cropland)	UN 2020
2	2.1.2 Prevalence of moderate or severe food insecurity in the population (Cereal production per capita)	Imported Cereal production	by Authors
3	3.9.1 Mortality rate attributed to household and ambient air pollution (PM25 concentration)	PM2.5 footprint	UN 2020
3	3.9.1 Mortality rate attributed to household and ambient air pollution (SO2 concentration)	SO2 footprint	UN 2020
3	3.4.1 Mortality rate attributed to cardiovascular disease, cancer, diabetes or chronic respiratory disease	Noncommunicable diseases (NCD) deaths embodied in meat trade	Chung et al 2021
3	3.9.2 Mortality rate attributed to unsafe water, unsafe sanitation and lack of hygiene (exposure to unsafe Water, Sanitation and Hygiene for All (WASH) services)	Nitrogen footprint (nitrogen potentially exportable to water bodies)	by Authors
3	3.9 By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination	Exports of hazardous pesticides	Sachs et al 2021
4	4.1 By 2030, ensure that all girls and boys complete free, equitable and quality primary and secondary education leading to relevant and effective learning outcomes	Children out of School (SHDB)	by Authors
4	4.7.1/12.8.1/13.3.1 Extent to which global citizenship education	International student flows	by Authors
5	5.5.2 Proportion of women in managerial positions	Gender equity (SHDB)	by Authors
5	5.c.1 Proportion of countries with systems to track and make public allocations for gender equality and women's empowerment	Aids for Women development	by Authors
6	6.3.2 Proportion of bodies of water with good ambient water quality	Nitrogen footprint (nitrogen potentially exportable to water bodies)	Vanham et al 2019; Wiedmann and Allen 2021
6	6.4.1 Change in water-use (WU) efficiency over time	Water footprint	UN 2020; Xu et al 2020; Vanham et al 2019; Wiedmann and Allen 2021
6	6.4.2 Level of water stress: freshwater consumption as a proportion of available freshwater resources (WR)	Water footprint	UN 2020; Xu et al 2020; Vanham et al

SDG	SDG Indicator	Spillover indicators	References
			2019; Wiedmann and Allen 2021
7	7.1.2 Proportion of population with primary reliance on clean fuels and technology	Energy footprint (renewable energy)	UN 2020
7	7.2.1 Renewable energy share in the total final energy consumption	Energy footprint (renewable energy)	UN 2020; Xu et al 2020
7	7.3.1 Energy intensity measured in terms of primary energy and GDP (low energy intensity indicates high SDG indicator score)	Energy footprint (primary energy)	UN 2020; Xu et al 2020; Vanham et al 2019; Wiedmann and Allen 2021
8	8.1.1 Annual growth rate of real GDP per capita	GDP embodied in trade	Sachs et al 2020
8	8.5.1 Average hourly earnings of employees	Wages footprint	by Authors
8	8.5.2 Unemployment rate, by sex, age and persons with disabilities	Employment footprint	Wiedmann and Allen 2021
8	8.8.1-1 Fatal occupational injuries per 100,000 workers	Occupational Safety and Health footprint (fatal accidents)	UN 2020; Sachs et al 2020; Wiedmann and Allen 2021
8	8.8.1-2 Non-fatal occupational injuries per 100,000 workers	Occupational Safety and Health footprint (non-fatal accidents)	UN 2020; Sachs et al 2020; Wiedmann and Allen 2021
9	9.4.1-1 CO2 emission per unit of value added	Carbon footprint	UN 2020; Xu et al 2020; Vanham et al 2019; Wiedmann and Allen 2021
9	9.4.1-2 CO2 emissions from fuel combustion	Carbon footprint	Xu et al 2020; Sachs et al 2018
10	10.4.1 Labour share of GDP, comprising wages and social protection transfers	Wages footprint	by Authors
11	11.6.2-1 Annual mean levels of fine particulate matter (e.g., PM2.5 and PM10) in cities (population weighted)	PM2.5 footprint	UN 2020; Wiedmann and Allen 2021

SDG	SDG Indicator	Spillover indicators	References
11	11.6.2-2 Annual mean levels of fine particulate matter (e.g., PM2.5 and PM10) in cities (population weighted)	PM10 footprint	UN 2020; Vanham et al 2019; Wiedmann and Allen 2021
12	12.2.1 Material footprint per capita (SO_2 footprint per capita)	SO_2 footprint	Sachs et al 2020
12	12.2.1 Material footprint per capita	Material footprint	UN 2020; Xu et al 2020; Vanham et al 2019; Wiedmann and Allen 2021
12	12.2.1 Material footprint per GDP (low material intensity indicates high SDG indicator score)	Material footprint	UN 2020; Xu et al 2020; Vanham et al 2019
12	12.2.1 Material footprint per GDP (Nitrogen footprint per GDP)	Nitrogen footprint - (Total, i.e., NO_x, NH_3 and N_2O emissions to air, and the direct nitrogen emissions to water)	UN 2020; Sachs et al 2020
13	13.2.2 Total greenhouse gas emissions per year	GHG footprint	UN 2020; Wiedmann and Allen 2021
13	13.2.s CO_2 emissions intensity of areas under forest management ($GtCO_2$-equivalent per ha)	Carbon footprint	Xu et al 2020; SDSN, 2015; Vanham et al 2019
14	14.1.1 Index of coastal eutrophication (Nitrogen footprint per ha of cropland as a proxy)	Nitrogen footprint (nitrogen potentially exportable to water bodies)	UN 2020; Vanham et al 2019; Wiedmann and Allen 2021
14	14.1.1 Index of coastal eutrophication (Phosphorus footprint per ha of cropland as a proxy)	Phosphorus footprint (to water bodies)	Vanham et al 2019; Wiedmann and Allen 2021
15	15.1.1 Forest area as a proportion of total land area (high value indicates high SDG indicator score)	Land footprint (forest land)	UN 2020; Xu et al 2020; Vanham et al 2019; Wiedmann

SDG	SDG Indicator	Spillover indicators	References
			and Allen 2021
15	15.2.1 Progress towards sustainable forest management (forest area net change rate as a measure)	Land footprint (forest land)	UN 2020; Xu et al 2020
15	15.5 Take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity and, by 2020, protect and prevent the extinction of threatened species	Biodiversity footprint	by Authors
16; 5	16.2.2 Number of victims of human trafficking per 100,000 population	Human trafficking	by Authors
16	16.4.2 Proportion of seized, found or surrendered arms whose illicit origin or context has been traced or established by a competent authority in line with international instruments	Transfers of major conventional weapons	UN 2020; Sachs et al 2020
16	16.5 Substantially reduce corruption and bribery in all their forms	Corruption footprint	UN 2020
17	17.2.1 Net official development assistance, total and to least developed countries, as a proportion of the Organization for Economic Cooperation and Development (OECD) Development Assistance Committee donors' gross national income (GNI)	International concessional public finance, including official development assistance	Sachs et al 2021
17	17.3.1 Foreign direct investment as a proportion of gross national income	Foreign direct investment	by Authors
17	17.3.1 Official development assistance as a proportion of gross national income	International concessional public finance, including official development assistance	by Authors

Supplementary Table 2. Spillover indicators and detailed data sources

Spillover indicators	Source	Source link	References
Carbon footprint	Edgar_v5.0	https://edgar.jrc.ec.europa.eu/overview.php?v=50_GHG	/
GHG footprint	Edgar_v5.0	https://edgar.jrc.ec.europa.eu/overview.php?v=50_GHG	/
NOx footprint	Edgar_v5.0	https://edgar.jrc.ec.europa.eu/overview.php?v=50_AP	/
PM10 footprint	Edgar_v5.0	https://edgar.jrc.ec.europa.eu/overview.php?v=50_AP	/
PM2.5 footprint	Edgar_v5.0	https://edgar.jrc.ec.europa.eu/overview.php?v=50_AP	Liang et al. 2017; Zhang et al. 2017; Xiao et al. 2018b
SO2 footprint	Edgar_v5.0	https://edgar.jrc.ec.europa.eu/overview.php?v=50_AP	Zhang et al. 2017
Water footprint	Aquastat	http://www.fao.org/nr/water/aquastat/data/query/results.html	Wiedmann and Lenzen 2018
Scarce water footprint	AWEAR	http://www.wulca-waterlca.org/aware.html	Lenzen et al 2013; Lenzen et al 2020
Energy footprint (total)	IEA	https://stats.oecd.org/BrandedView.aspx?oecd_bv_id=enestats-data-en&doi=data-00510-en	Chen et al 2018
Energy footprint (primary energy)	IEA	https://stats.oecd.org/BrandedView.aspx?oecd_bv_id=enestats-data-en&doi=data-00510-en	Xu et al 2020
Energy footprint (renewable energy)	IEA	https://stats.oecd.org/BrandedView.aspx?oecd_bv_id=enestats-data-en&doi=data-00510-en	Xu et al 2020
Land footprint (cropland)	FAOSTAT	http://www.fao.org/faostat/en/#data/RL	Yu et al. 2013
Land footprint (forest land)	FAOSTAT	http://www.fao.org/faostat/en/#data/RL	Yu et al. 2013
Employment footprint	ILOSTAT	https://ilostat.ilo.org	Alsamawi et al. 2014
Wage footprint	ILOSTAT	https://ilostat.ilo.org	Alsamawi et al. 2014
Nitrogen footprint - (Total)	FAO and IFA		Oita et al 2016
Nitrogen footprint (NOx, NH3 and N2O emissions to air)	FAOSTAT	http://www.fao.org/faostat/en/#data/RL	Oita et al 2018
Nitrogen footprint (nitrogen potentially exportable to water bodies)	FAOSTAT	http://www.fao.org/faostat/en/#data/RL	Oita et al 2019

Spillover indicators	Source	Source link	References
GINI footprint	World Bank	https://data.worldbank.org/indicator/SI.POV.GINI	Alsamawi et al 2014
Corruption footprint	Corruption perceptions index; CCI; and IPB indices	https://www.transparency.org/research/cpi/overview	Xiao et al. 2018a
Occupational Safety and Health footprint (fatal accidents)	ILOSTAT	https://ilostat.ilo.org	Alsamawi et al. 2017
Occupational Safety and Health footprint (non-fatal accidents)	ILOSTAT	https://ilostat.ilo.org	Alsamawi et al. 2017
Material footprint		https://www.resourcepanel.org/global-material-flows-database	Xu et al 2020
Phosphorus footprint (total)			Kunyu et al 2021
Phosphorus footprint (to water bodies)			Kunyu et al 2021
GDP embodied in trade			Xu et al 2020
Biodiversity footprint			Marques et al 2017
Poverty footprint	Based on employment and salary		Alsamawi et al. 2014
International concessional public finance, including official development assistance	OECD	https://data.oecd.org/oda/net-oda.htm	SDSN 2020
Foreign direct investment	World Bank	https://data.worldbank.org/	/
Investments in conflict prevention and peacekeeping	Stockholm International Peace Research Institute (SIPRI)	https://www.sipri.org/databases/pko	SDSN 2020
Transfers of major conventional weapons	Stockholm International Peace Research Institute (SIPRI)	https://www.sipri.org/databases/armstransfers	SDSN 2020
Human trafficking	The Counter-Trafficking Data Collaborative (CTDC)	https://www.ctdatacollaborative.org/download-global-dataset	Constructed by Authors
International student flows	UNESCO	http://data.uis.unesco.org/	Hou et al 2020

Spillover indicators	Source	Source link	References
Child Labor footprint	SHDB	http://www.socialhotspot.org/purchase-shdb-licences.html	Norris and Norris 2015
Forced Labor footprint	SHDB	http://www.socialhotspot.org/purchase-shdb-licences.html	Norris and Norris 2015
Exports of hazardous pesticides	FAO	http://www.fao.org/faostat/en/#data/RT/metadata	SDSN 2021
Chemical footprint (hazardous pesticides + PM2.5 + PM10)	Edgar_v5.0	https://edgar.jrc.ec.europa.eu/overview.php?v=50_AP	/
Imported Cereal production	FAO	http://www.fao.org/faostat/	/
Noncommunicable diseases (NCD) deaths embodied in the meat trade	GHDx	http://ghdx.healthdata.org	Chung et al 2021

Country list and country groups

The 189 countries were grouped into 65 high-income countries, 47 upper-middle-income countries, 48 lower-middle-income countries, and 30 low-income countries based on World Bank's classification (Supplementary Table 3). We then calculated the average SDG score for each country in each group, again without weighting for country population or gross domestic product. We also classified international interactions into "adjacent" ones and "distant" ones based on the geographical relationship between countries (Xu et al. 2020b). For example, interactions between countries that share land or maritime borders were deemed as adjacent ones. In all other cases, interactions between two countries or regions were deemed as distant ones (see Supplementary Table 4 for a list of countries and territories by land and maritime borders) (Charney et al. 1993; Anderson 2003; Xu et al. 2020b). This allowed us to assess the impacts of adjacent versus distant impacts on SDG scores in the metacoupled world system.

Supplementary Table 3. Country list.

Name	ISO3	Income Group	Flag
Aruba	ABW	High income	
Afghanistan	AFG	Low income	
Angola	AGO	Upper middle income	
Albania	ALB	Lower middle income	
Andorra	AND	High income	
Netherlands Antilles	ANT	High income	
UAE	ARE	High income	
Argentina	ARG	Upper middle income	
Armenia	ARM	Lower middle income	
Antigua	ATG	Upper middle income	
Australia	AUS	High income	
Austria	AUT	High income	
Azerbaijan	AZE	Upper middle income	
Burundi	BDI	Low income	
Belgium	BEL	High income	
Benin	BEN	Low income	
Burkina Faso	BFA	Low income	
Bangladesh	BGD	Low income	
Bulgaria	BGR	Upper middle income	
Bahrain	BHR	High income	
Bahamas	BHS	High income	
Bosnia and Herzegovina	BIH	Upper middle income	
Belarus	BLR	Upper middle income	
Belize	BLZ	Lower middle income	
Bermuda	BMU	High income	
Bolivia	BOL	Lower middle income	
Brazil	BRA	Upper middle income	
Barbados	BRB	High income	
Brunei	BRN	High income	
Bhutan	BTN	Lower middle income	
Botswana	BWA	Upper middle income	
Central African Republic	CAF	Low income	
Canada	CAN	High income	
Switzerland	CHE	High income	
Chile	CHL	Upper middle income	
China	CHN	Upper middle income	
Cote dIvoire	CIV	Lower middle income	
Cameroon	CMR	Lower middle income	
DR Congo	COD	Low income	
Congo	COG	Lower middle income	
Colombia	COL	Upper middle income	
Cape Verde	CPV	Lower middle income	
Costa Rica	CRI	Upper middle income	
Cuba	CUB	Upper middle income	
Curaçao	CUW	High income	
Cayman Islands	CYM	High income	
Cyprus	CYP	High income	

Name	ISO3	Income Group	Flag
Czech Republic	CZE	High income	
Germany	DEU	High income	
Djibouti	DJI	Lower middle income	
Denmark	DNK	High income	
Dominican Republic	DOM	Upper middle income	
Algeria	DZA	Upper middle income	
Ecuador	ECU	Upper middle income	
Egypt	EGY	Lower middle income	
Eritrea	ERI	Low income	
Spain	ESP	High income	
Estonia	EST	High income	
Ethiopia	ETH	Low income	
Finland	FIN	High income	
Fiji	FJI	Lower middle income	
France	FRA	High income	
Gabon	GAB	Upper middle income	
UK	GBR	High income	
Georgia	GEO	Lower middle income	
Ghana	GHA	Lower middle income	
Guinea	GIN	Low income	
Gambia	GMB	Low income	
Greece	GRC	High income	
Greenland	GRL	High income	
Guatemala	GTM	Lower middle income	
Guyana	GUY	Lower middle income	

Name	ISO3	Income Group	Flag
Hong Kong	HKG	High income	
Honduras	HND	Lower middle income	
Croatia	HRV	High income	
Haiti	HTI	Low income	
Hungary	HUN	High income	
Indonesia	IDN	Lower middle income	
India	IND	Lower middle income	
Ireland	IRL	High income	
Iran	IRN	Upper middle income	
Iraq	IRQ	Lower middle income	
Iceland	ISL	High income	
Israel	ISR	High income	
Italy	ITA	High income	
Jamaica	JAM	Upper middle income	
Jordan	JOR	Upper middle income	
Japan	JPN	High income	
Kazakhstan	KAZ	Upper middle income	
Kenya	KEN	Low income	
Kyrgyzstan	KGZ	Low income	
Cambodia	KHM	Low income	
South Korea	KOR	High income	
Kuwait	KWT	High income	
Laos	LAO	Lower middle income	
Lebanon	LBN	Upper middle income	
Liberia	LBR	Low income	

Name	ISO3	Income Group	Flag
Libya	LBY	Upper middle income	
Liechtenstein	LIE	High income	
Sri Lanka	LKA	Lower middle income	
Lesotho	LSO	Lower middle income	
Lithuania	LTU	Upper middle income	
Luxembourg	LUX	High income	
Latvia	LVA	Upper middle income	
Macao SAR	MAC	High income	
Morocco	MAR	Lower middle income	
Monaco	MCO	High income	
Moldova	MDA	Lower middle income	
Madagascar	MDG	Low income	
Maldives	MDV	Upper middle income	
Mexico	MEX	Upper middle income	
TFYR Macedonia	MKD	Upper middle income	
Mali	MLI	Low income	
Malta	MLT	High income	
Myanmar	MMR	Low income	
Montenegro	MNE	Upper middle income	
Mongolia	MNG	Lower middle income	
Mozambique	MOZ	Low income	
Mauritania	MRT	Low income	
Mauritius	MUS	Upper middle income	
Malawi	MWI	Low income	

Name	ISO3	Income Group	Flag
Malaysia	MYS	Upper middle income	
Namibia	NAM	Upper middle income	
New Caledonia	NCL	High income	
Niger	NER	Low income	
Nigeria	NGA	Lower middle income	
Nicaragua	NIC	Lower middle income	
Netherlands	NLD	High income	
Norway	NOR	High income	
Nepal	NPL	Low income	
New Zealand	NZL	High income	
Oman	OMN	High income	
Pakistan	PAK	Lower middle income	
Panama	PAN	Upper middle income	
Peru	PER	Upper middle income	
Philippines	PHL	Lower middle income	
Papua New Guinea	PNG	Lower middle income	
Poland	POL	High income	
North Korea	PRK	Low income	
Portugal	PRT	High income	
Paraguay	PRY	Lower middle income	
Gaza Strip	PSE	Lower middle income	
French Polynesia	PYF	High income	
Qatar	QAT	High income	
Romania	ROU	Upper middle income	

Name	ISO3	Income Group	Flag
Russia	RUS	Upper middle income	
Rwanda	RWA	Low income	
Saudi Arabia	SAU	High income	
Sudan	SDN	Lower middle income	
Senegal	SEN	Lower middle income	
Singapore	SGP	High income	
Sierra Leone	SLE	Low income	
El Salvador	SLV	Lower middle income	
San Marino	SMR	High income	
Somalia	SOM	Low income	
Serbia	SRB	Upper middle income	
South Sudan	SSD	Low income	
Sao Tome and Principe	STP	Lower middle income	
Former USSR	SUN	Low income	
Suriname	SUR	Upper middle income	
Slovakia	SVK	High income	
Slovenia	SVN	High income	
Sweden	SWE	High income	
Swaziland	SWZ	Lower middle income	
Seychelles	SYC	Upper middle income	
Syria	SYR	Lower middle income	
Chad	TCD	Low income	
Togo	TGO	Low income	

Name	ISO3	Income Group	Flag
Thailand	THA	Upper middle income	
Tajikistan	TJK	Low income	
Turkmenistan	TKM	Upper middle income	
Trinidad and Tobago	TTO	High income	
Tunisia	TUN	Upper middle income	
Turkey	TUR	Upper middle income	
Taiwan	TWN	High income	
Tanzania	TZA	Low income	
Uganda	UGA	Low income	
Ukraine	UKR	Lower middle income	
Uruguay	URY	Upper middle income	
USA	USA	High income	
Uzbekistan	UZB	Lower middle income	
Venezuela	VEN	Upper middle income	
British Virgin Islands	VGB	High income	
Viet Nam	VNM	Lower middle income	
Vanuatu	VUT	Lower middle income	
Samoa	WSM	Lower middle income	
Yemen	YEM	Lower middle income	
South Africa	ZAF	Upper middle income	
Zambia	ZMB	Lower middle income	
Zimbabwe	ZWE	Low income	

Supplementary Table 4. Countries and their adjacent neighbors (share land or maritime borders)

Name	ISO3	Neighbors
Aruba	ABW	CUW;DOM;VEN
Afghanistan	AFG	CHN;IRN;PAK;TJK;TKM;UZB
Angola	AGO	COD;COG;NAM;ZMB
Albania	ALB	GRC;ITA;MNE;MKD
Andorra	AND	FRA;ESP
Netherlands Antilles	ANT	DOM;NLD;VEN;ABW
United Arab Emirates	ARE	IRN;OMN;QAT;SAU
Argentina	ARG	BOL;BRA;CHL;PRY;URY
Armenia	ARM	AZE;GEO;IRN;TUR
Antigua and Barbuda	ATG	FRA
Australia	AUS	IDN;NZL;PNG
Austria	AUT	CZE;DEU;HUN;ITA;LIE;SVK;SVN;CHE
Azerbaijan	AZE	ARM;GEO;IRN;KAZ;TUR;TKM
Burundi	BDI	COD;RWA;TZA
Belgium	BEL	FRA;DEU;LUX;NLD;GBR
Benin	BEN	BFA;NER;NGA;TGO
Burkina Faso	BFA	BEN;CIV;GHA;MLI;NER;TGO
Bangladesh	BGD	MMR;IND
Bulgaria	BGR	GRC;MKD;ROU;SRB;TUR
Bahrain	BHR	IRN;QAT;SAU
Bahamas	BHS	CUB;HTI;USA
Bosnia and Herzegovina	BIH	HRV;MNE;SRB
Belarus	BLR	LVA;LTU;POL;RUS;UKR
Belize	BLZ	GTM;HND;MEX
Bermuda	BMU	None
Bolivia	BOL	ARG;BRA;CHL;PRY;PER
Brazil	BRA	ARG;BOL;COL;FRA;GUY;PRY;PER;SUR;URY;VEN
Barbados	BRB	FRA;GUYTTO;VEN

Name	ISO3	Neighbors
Brunei	BRN	CHN;MYS;PHL;TWN;VNM
Bhutan	BTN	CHN;IND
Botswana	BWA	NAM;ZAF;ZMB;ZWE
Central African Republic	CAF	CMR;TCD;COD;COG;SSD;SDN
Canada	CAN	USA;GRL
Switzerland	CHE	AUT;FRA;ITA;LIE;DEU
Chile	CHL	ARG;BOL;PER
People's Republic of China	CHN	AFG;BTN;BRN;IND;IDN;JPN;KAZ;PRK;KOR;KGZ;LAO;MYS;MNG;MMR;NPL;PAK;PHL;RUS;TJK;VNM;HKG;MAC;TWN
Côte d'Ivoire	CIV	BFA;GHA;GIN;LBR;MLI
Cameroon	CMR	CAF;TCD;COGGAB;NGA
Democratic Republic of the Congo	COD	AGO;BDI;CAF;COG;RWA;SSD;TZA;UGA;ZMB
Republic of the Congo	COG	AGO;CMR;CAF;COD;GAB
Colombia	COL	BRA;CRI;DOM;ECU;HTI;JAM;NIC;PAN;PER;VEN
Cape Verde	CPV	GMB;MRT;SEN
Costa Rica	CRI	COL;ECU;NIC;PAN
Cuba	CUB	BHS;HTI;HND;JAM;MEX;USA;CYM
Curaçao	CUW	DOM;NLD;VEN;ABW
Cayman Islands	CYM	CUB;HND;JAM
Cyprus	CYP	EGY;GRC;ISR;LBN;SYR;TUR
Czech Republic	CZE	AUT;DEU;POL;SVK
Germany	DEU	AUT;BEL;CZE;DNK;FRA;LUX;NLD;POL;SWE;CHE;GBR
Djibouti	DJI	ERI;ETH;SOM;YEM

Name	ISO3	Neighbors
Denmark	DNK	DEU;NOR;POL;SWE;GBR
Dominican Republic	DOM	COL;HTI;VEN;ABW;CUW
Algeria	DZA	ITA;LBY;MLI;MRT;MAR;NER;ESP;TUN
Ecuador	ECU	COL;CRI;PER
Egypt	EGY	CYP;GRC;ISR;JOR;LBY;SAU;SDN;TUR;PSE
Eritrea	ERI	DJI;SAU;SDN;ETH;YEM
Spain	ESP	DZA;AND;FRA;ITA;MAR;PRT
Estonia	EST	FIN;LVA;RUS;SWE
Ethiopia	ETH	DJI;ERI;KEN;SOM;SSD;SDN
Finland	FIN	EST;NOR;RUS;SWE
Fiji	FJI	NZLVUT;NCL
France	FRA	AND;ATG;BRB;BEL;BRADEU;ITA;LUX;MDG;MUS;MCOESP;CHE;SUR;GBR;VEN
Gabon	GAB	CMR;COGSTP
United Kingdom	GBR	BEL;DNK;FRA;DEU;IRL;NLD;NOR;ESP
Georgia	GEO	ARM;AZE;RUS;TUR
Ghana	GHA	BFA;CIV;TGO
Guinea	GIN	CIVLBR;MLI;SEN;SLE
The Gambia	GMB	CPV;SEN
Greece	GRC	ALB;BGR;CYP;EGY;ITA;LBY;MKD;TUR
Greenland	GRL	CAN;ISL
Guatemala	GTM	BLZ;SLV;HND;MEX
Guyana	GUY	BRB;BRA;SUR;TTO;VEN
Hong Kong	HKG	CHN;MAC
Honduras	HND	BLZ;CUB;SLV;GTM;JAM;MEX;NIC;CYM
Croatia	HRV	BIH;HUN;ITA;MNE;SRB;SVN
Haiti	HTI	BHS;COL;CUB;DOM;JAM
Hungary	HUN	AUT;HRV;ROU;SRB;SVK;SVN;UKR
Indonesia	IDN	AUS;CHNIND;MYSPNG;PHL;SGP;TWN;THA;VNM

Name	ISO3	Neighbors
India	IND	BGD;BTN;MMR;CHN;IDN;MDV;NPL;PAK;LKA;THA
Ireland	IRL	GBR
Iran	IRN	AFG;ARM;AZE;BHR;IRQ;KWT;OMN;PAK;QAT;SAU;TUR;TKM;ARE
Iraq	IRQ	IRN;JOR;KWT;SAU;SYR;TUR
Iceland	ISL	GRL
Israel	ISR	CYP;EGY;JOR;LBN;SYR;PSE
Italy	ITA	ALB;DZA;AUT;HRV;FRA;GRC;LBY;MLT;MNE;SMR;SVN;ESP;CHE;TUN
Jamaica	JAM	COL;CUB;HTI;HND;NIC;CYM
Jordan	JOR	EGY;IRQ;ISR;SAU;SYR;PSE
Japan	JPN	CHN;KORPHL;RUSTWN
Kazakhstan	KAZ	AZE;CHN;KGZ;RUS;UZB
Kenya	KEN	ETH;SOM;SSD;TZA;UGA
Kyrgyzstan	KGZ	CHN;KAZ;TJK;UZB
Cambodia	KHM	LAO;THA
South Korea	KOR	CHN;JPN;PRK
Kuwait	KWT	IRN;IRQ;SAU
Laos	LAO	MMR;KHM;CHN;THA;VNM
Lebanon	LBN	CYP;ISR;SYR
Liberia	LBR	CIV;GIN;SLE
Libya	LBY	DZA;TCD;EGY;GRC;ITA;MLT;NER;SDN;TUN;TUR
Liechtenstein	LIE	AUT;CHE
Sri Lanka	LKA	IND;MDV
Lesotho	LSO	ZAF
Lithuania	LTU	BLR;LVA;POL;RUS;SWE
Luxembourg	LUX	BEL;FRA;DEU
Latvia	LVA	BLR;EST;LTU;RUS;SWE
Macau	MAC	CHN;HKG
Morocco	MAR	DZA;PRT;ESP

Name	ISO3	Neighbors
Monaco	MCO	FRA
Moldova	MDA	ROU;UKR
Madagascar	MDG	FRA;MUS;MOZ;SYC
Maldives	MDV	IND;LKA
Mexico	MEX	BLZ;CUB;GTM;HND;USA
North Macedonia	MKD	ALB;BGR;GRC;SRB
Mali	MLI	DZA;BFA;CIV;GIN;MRT;NER;SEN
Malta	MLT	ITA;LBY;TUN
Myanmar	MMR	BGD;CHN;IND;LAO;THA
Montenegro	MNE	ALB;BIH;HRV;ITA;SRB
Mongolia	MNG	CHN;RUS
Mozambique	MOZ	SWZ;MDG;MWI;ZAF;TZA;ZMB;ZWE
Mauritania	MRT	DZA;CPV;MLI;SEN
Mauritius	MUS	FRA;MDG;SYC
Malawi	MWI	MOZ;TZA;ZMB
Malaysia	MYS	BRN;CHN;IDN;PHL;SGP;THA;VNM;TWN
Namibia	NAM	AGO;BWA;ZAF;ZMB
New Caledonia	NCL	FJIVUT
Niger	NER	DZA;BEN;BFA;TCD;LBY;MLI;NGA
Nigeria	NGA	BEN;CMR;TCDNER;STP
Nicaragua	NIC	COL;CRI;SLV;HND;JAM;PAN
Netherlands	NLD	BEL;DEUGBR;VENCUW
Norway	NOR	DNK;FIN;RUS;SWE;GBR
Nepal	NPL	IND;CHN
New Zealand	NZL	AUS;FJI
Oman	OMN	IRN;PAK;SAU;ARE;YEM
Pakistan	PAK	AFG;CHN;IND;IRN;OMN
Panama	PAN	COL;CRI;NIC
Peru	PER	BOL;BRA;CHL;COL;ECU
Philippines	PHL	BRN;CHN;IDN;JPN;MYSVNM;TWN

Name	ISO3	Neighbors
Papua New Guinea	PNG	AUS;IDN
Poland	POL	BLR;CZE;DNK;DEU;LTU;RUS;SVK;SWE;UKR
North Korea	PRK	CHN;KOR;RUS
Portugal	PRT	MAR;ESP
Paraguay	PRY	ARG;BOL;BRA
Palestine	PSE	EGY;ISR;JOR
French Polynesia	PYF	None
Qatar	QAT	BHR;IRN;SAU;ARE
Romania	ROU	BGR;HUN;MDA;RUS;SRB;UKR
Russia	RUS	AZE;BLR;CHN;EST;FIN;GEO;JPN;PRK;LVA;LTU;MNG;NOR;POL;ROU;SWE;TUR;UKR;USA
Rwanda	RWA	BDI;COD;TZA;UGA
Saudi Arabia	SAU	BHR;EGY;ERI;IRN;IRQ;JOR;KWT;OMN;QAT;SDN;ARE;YEM
Sudan	SDN	CAF;TCD;EGY;ERI;ETH;LBY;SAU;SSD
Senegal	SEN	CPV;GMB;GINMLI;MRT
Singapore	SGP	IDN;MYS
Sierra Leone	SLE	GIN;LBR
El Salvador	SLV	GTM;HND;NIC
San Marino	SMR	ITA
Somalia	SOM	DJI;ETH;KEN;YEM
Serbia	SRB	BIH;BGR;HRV;HUN;MNE;MKD;ROU
South Sudan	SSD	CAF;COD;ETH;KEN;SDN;UGA
São Tomé and Príncipe	STP	GAB;NGA
Former USSR	SUN	AZE;BLR;CHN;EST;FIN;GEO;JPN;PRK;LVA;LTU;MNG;NOR;POL;ROU;SWE;TUR;UKR;USA
Suriname	SUR	BRA;FRA;GUY
Slovakia	SVK	AUT;CZE;HUN;POL;UKR
Slovenia	SVN	AUT;HRV;ITA;HUN

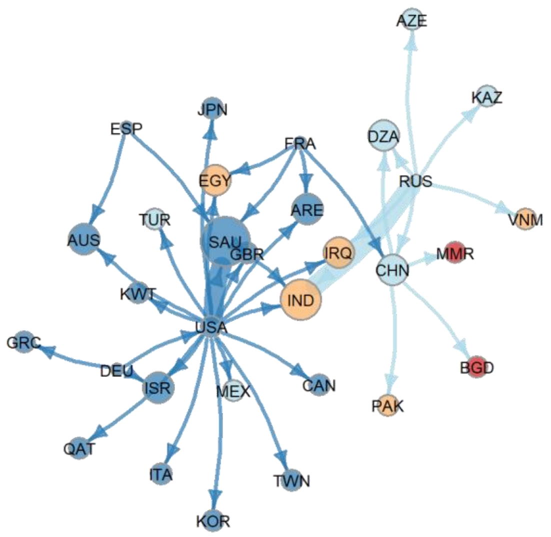
Name	ISO3	Neighbors
Sweden	SWE	DNK;EST;FIN;DEU;LVA;LTU;NOR;POL;RUS
Eswatini	SWZ	MOZ;ZAF
Seychelles	SYC	MDG;MUS;TZA
Syria	SYR	CYP;IRQ;ISR;JOR;LBN;TUR
Chad	TCD	CMR;CAF;LBY;NER;NGA;SDN
Togo	TGO	BEN;BFA;GHA
Thailand	THA	MMR;KHM;IND;IDN;LAO;MYS;VNM
Tajikistan	TJK	AFG;CHN;KGZ;UZB
Turkmenistan	TKM	AFG;AZE;UZB
Trinidad and Tobago	TTO	BRBGUYVEN
Tunisia	TUN	DZA;ITA;LBY;MLT
Turkey	TUR	ARM;AZE;BGR;CYP;EGY;GEO;GRC;IRN;IRQ;RUS;SYR;UKR;LBY
Taiwan	TWN	BRN;CHN;IDN;JPN;MYS;PHL;VNM
Tanzania	TZA	BDICOD;KEN;MWI;MOZ;RWA;SYC;UGA;ZMB

Name	ISO3	Neighbors
Uganda	UGA	COD;KEN;RWA;SSD;TZA
Ukraine	UKR	BLR;HUN;MDA;POL;ROU;RUS;SVK;TUR
Uruguay	URY	ARG;BRA
United States	USA	BHS;CAN;CUB;MEX;RUS
Uzbekistan	UZB	AFG;KAZ;KGZ;TJK;TKM
Venezuela	VEN	BRB;BRA;COLDOM;FRAGUY;NLDTTO;ABW;CUW
British Virgin Islands	VGB	None
Vietnam	VNM	BRN;IDN;LAO;MYS;PHL;TWN;THA
Vanuatu	VUT	FJINCL
Samoa	WSM	None
Yemen	YEM	DJI;ERI;OMN;SAU;SOM
South Africa	ZAF	BWA;SWZ;LSO;MOZ;NAM;ZWE
Zambia	ZMB	AGO;BWA;COD;MWI;MOZ;NAM;TZA;ZWE
Zimbabwe	ZWE	BWA;MOZ;ZAF;ZMB

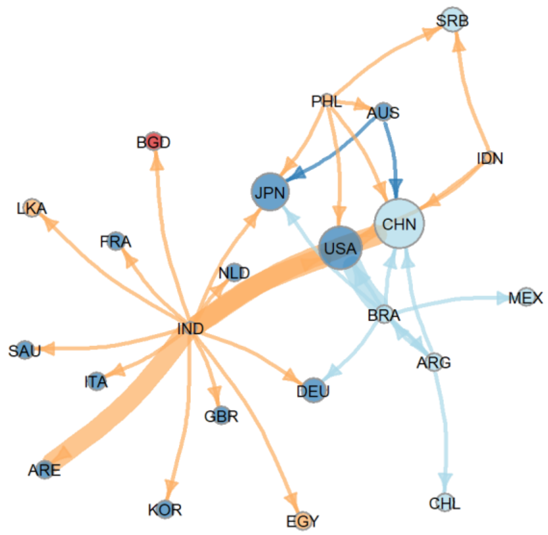
Supplementary Fig. 1. Network for each spillover.

Only the top 50 country pairs with the largest spillover flows are presented. The arrows point to the dominant influencers (or responsibility takers); The width of edges represents the magnitude of impact.

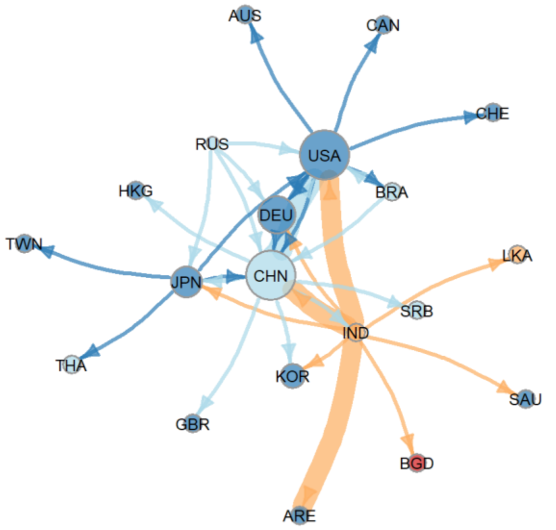
Weapon transfers



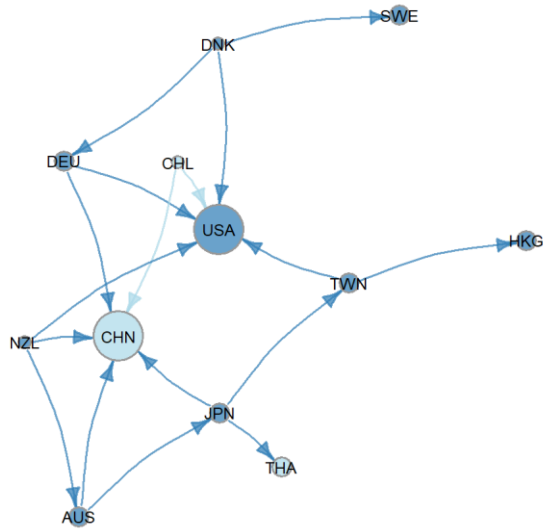
Biodiversity footprint



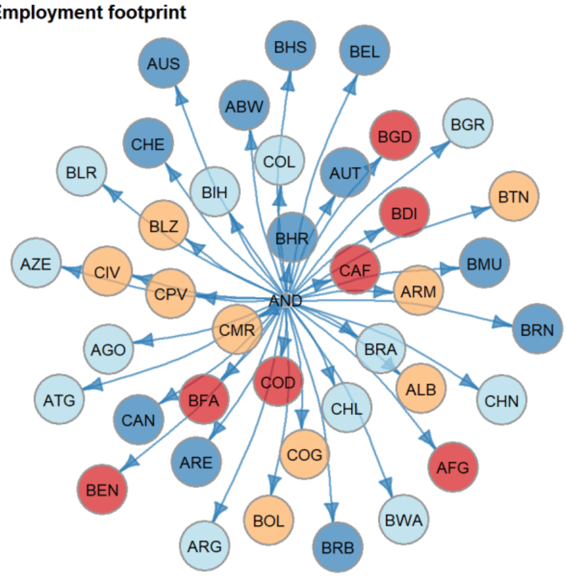
Carbon footprint



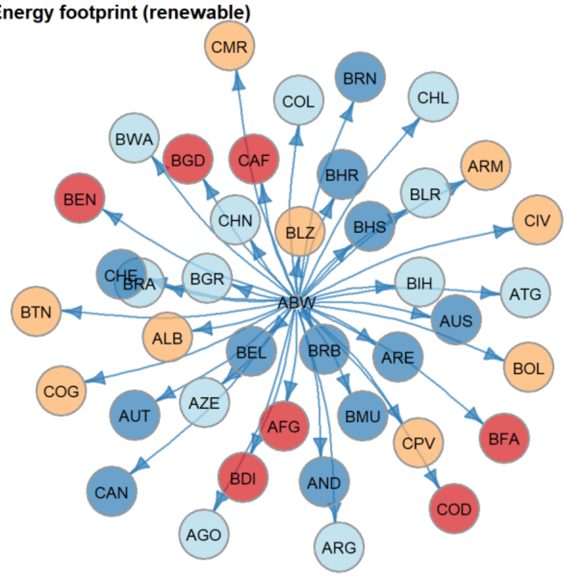
Corruption footprint



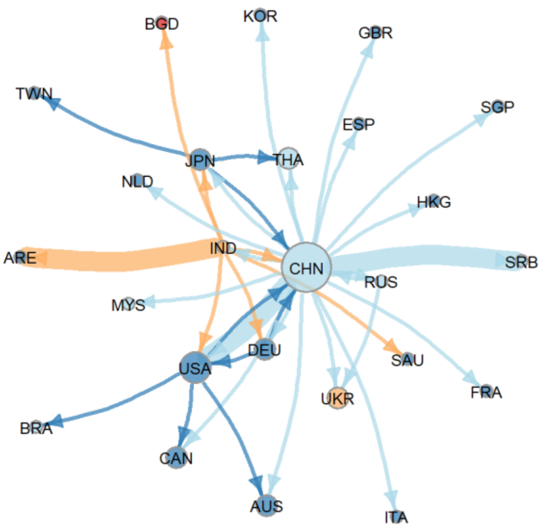
Employment footprint



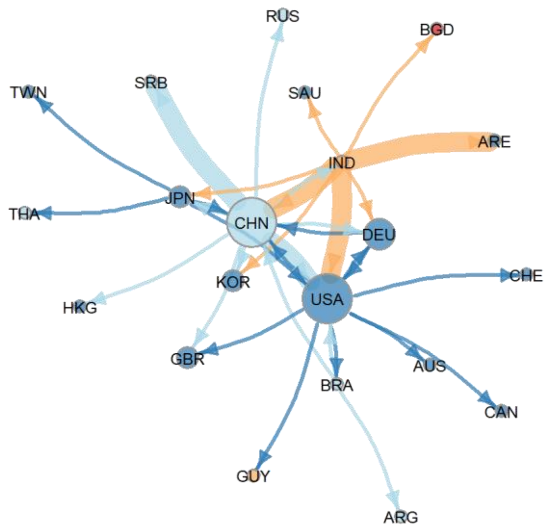
Energy footprint (renewable)



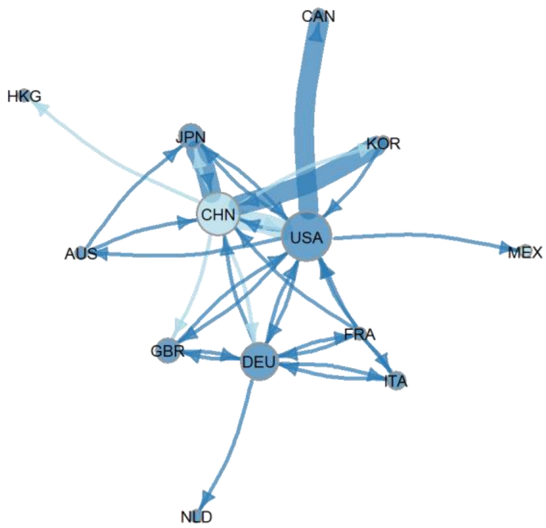
Energy footprint (primary)



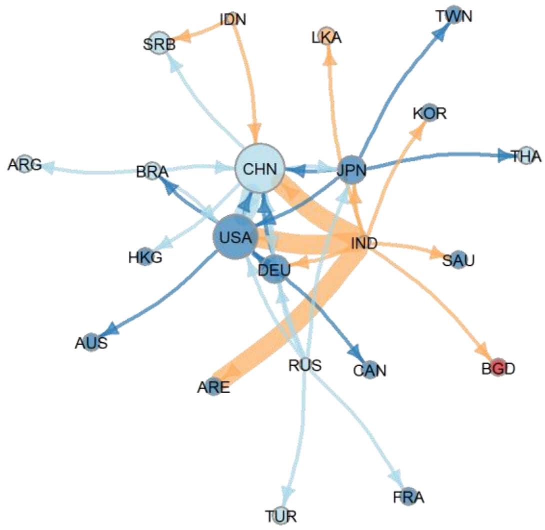
Energy footprint (total)



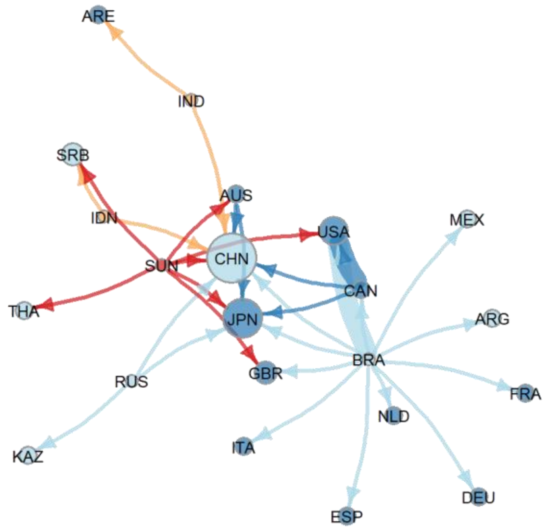
GDP footprint



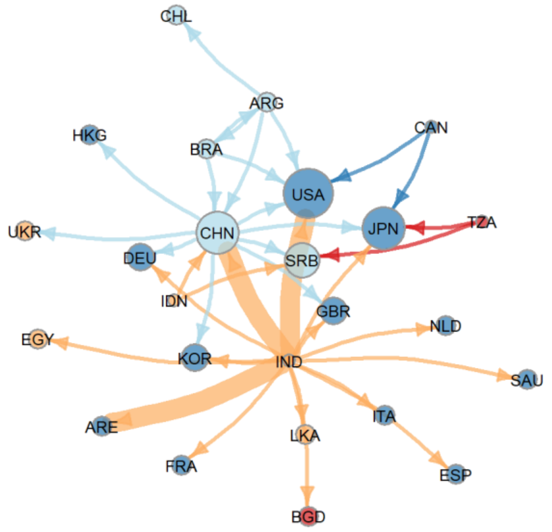
GHG footprint



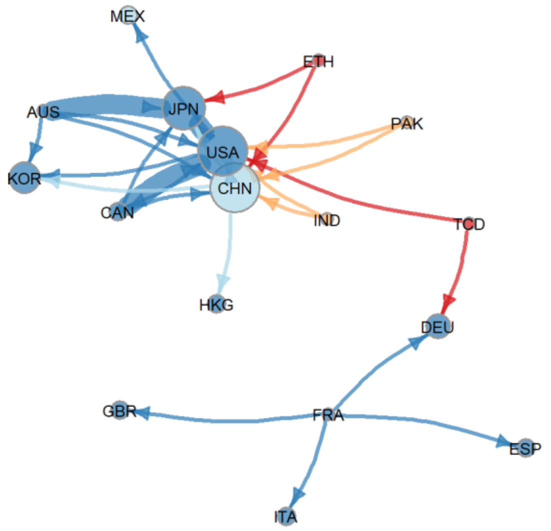
Land footprint (forest)



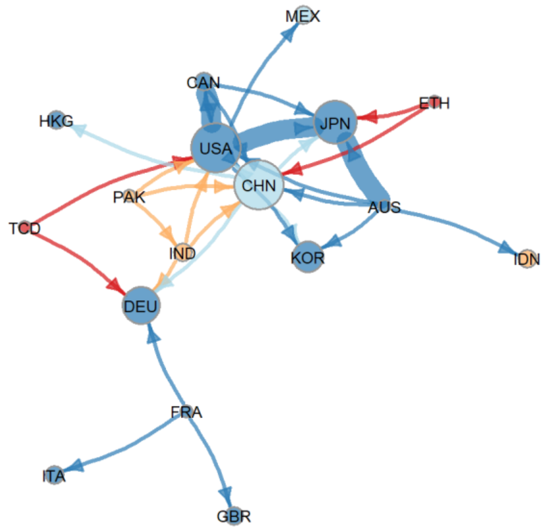
Land footprint (cropland)



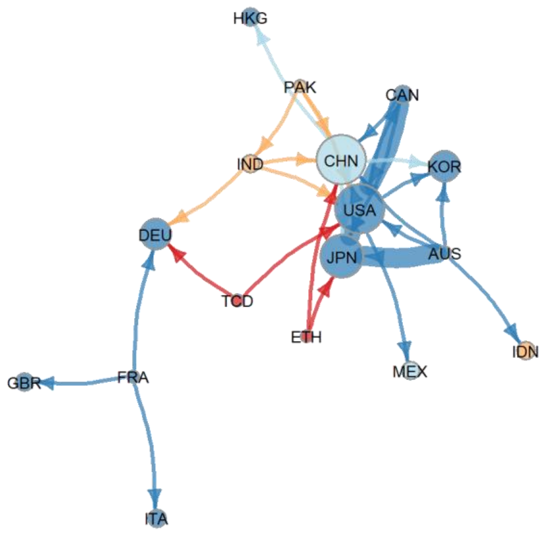
Nitrogen footprint (to air)



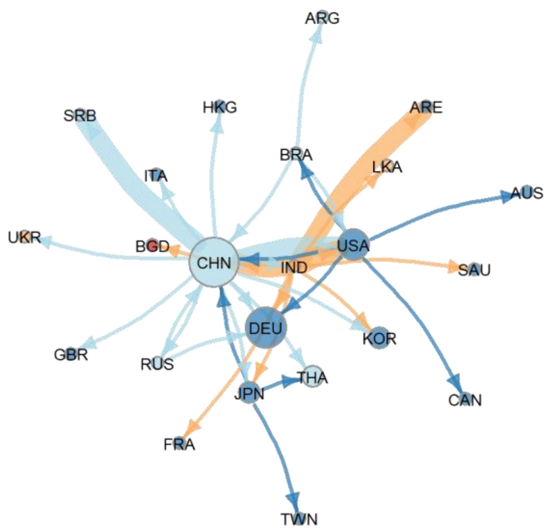
Nitrogen footprint (to water)



Nitrogen footprint (Total)

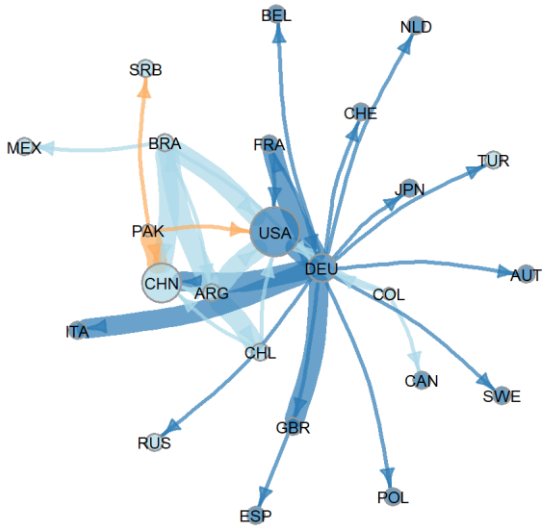


NOx footprint

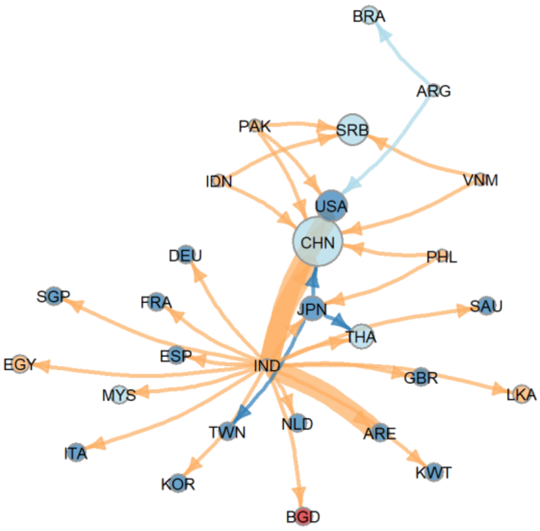


Fatal accidents footprint

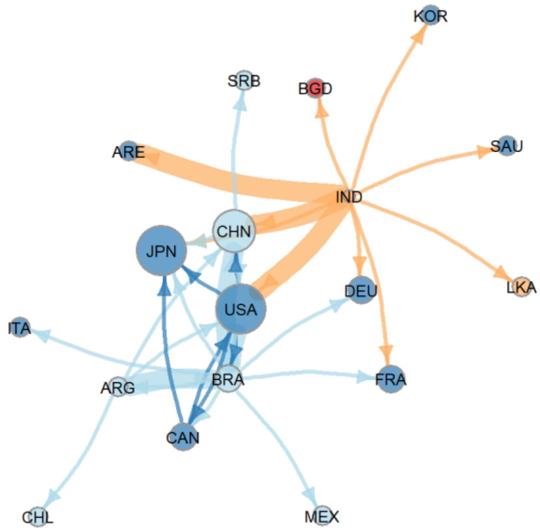
Non-fatal accidents footprint



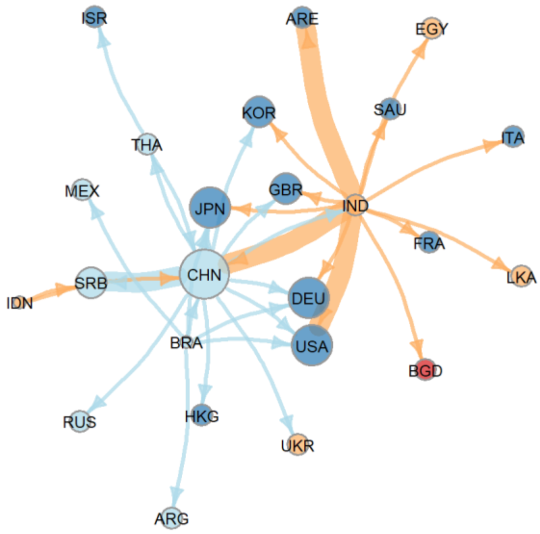
Phosphorus footprint (to water)



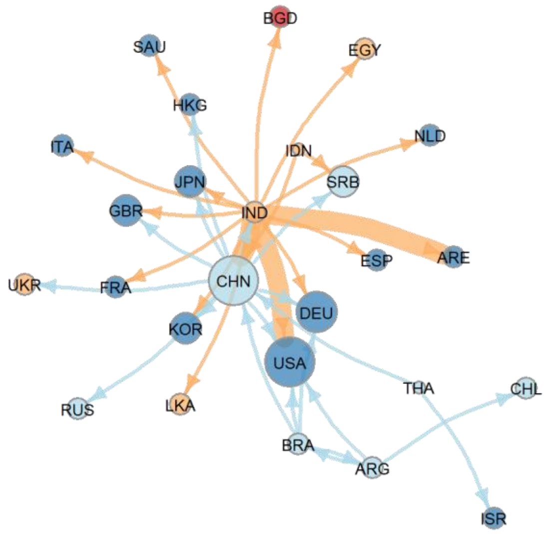
Phosphorus footprint (total)



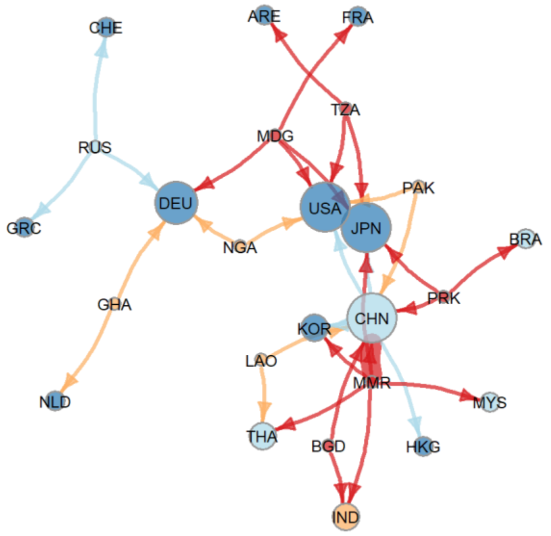
PM10 footprint



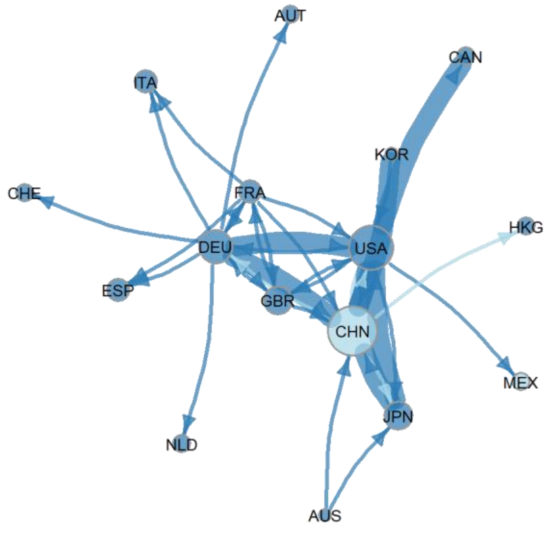
PM2.5 footprint



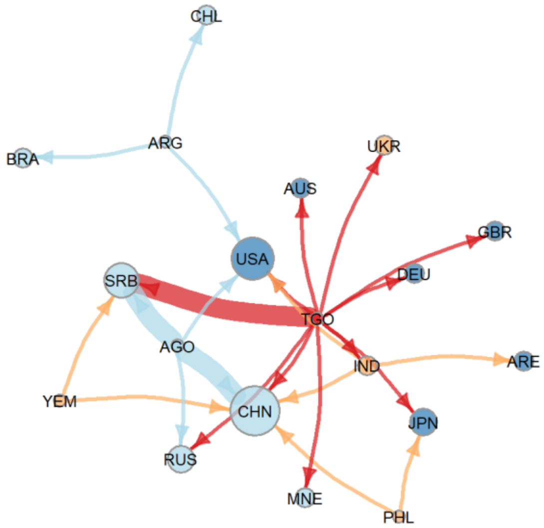
Poverty footprint



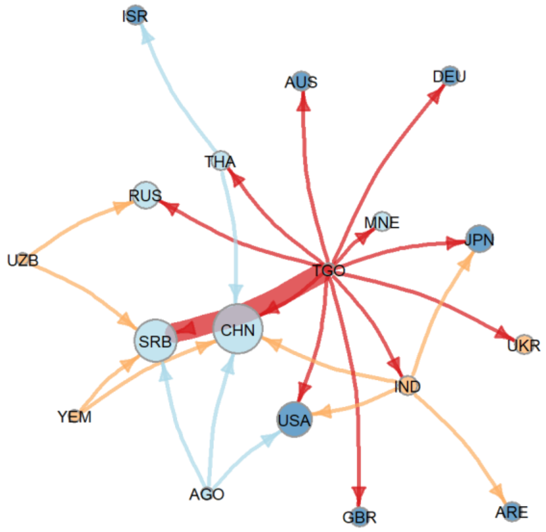
Wages footprint



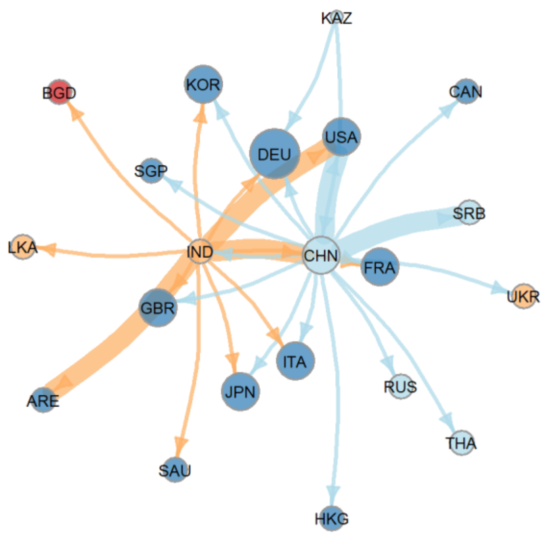
Child Labor footprint



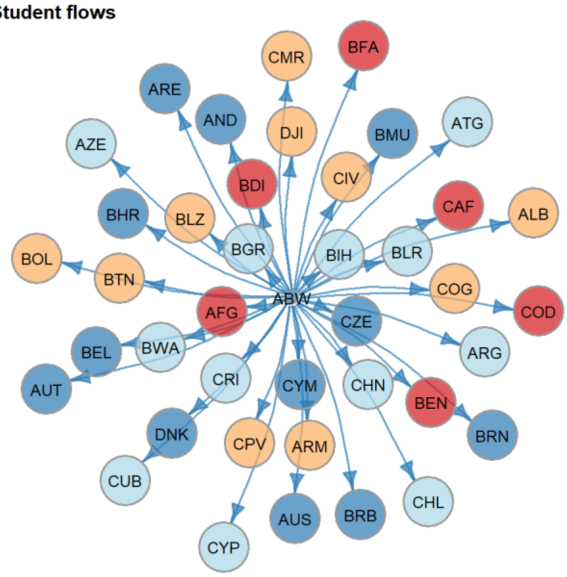
Forced Labor footprint

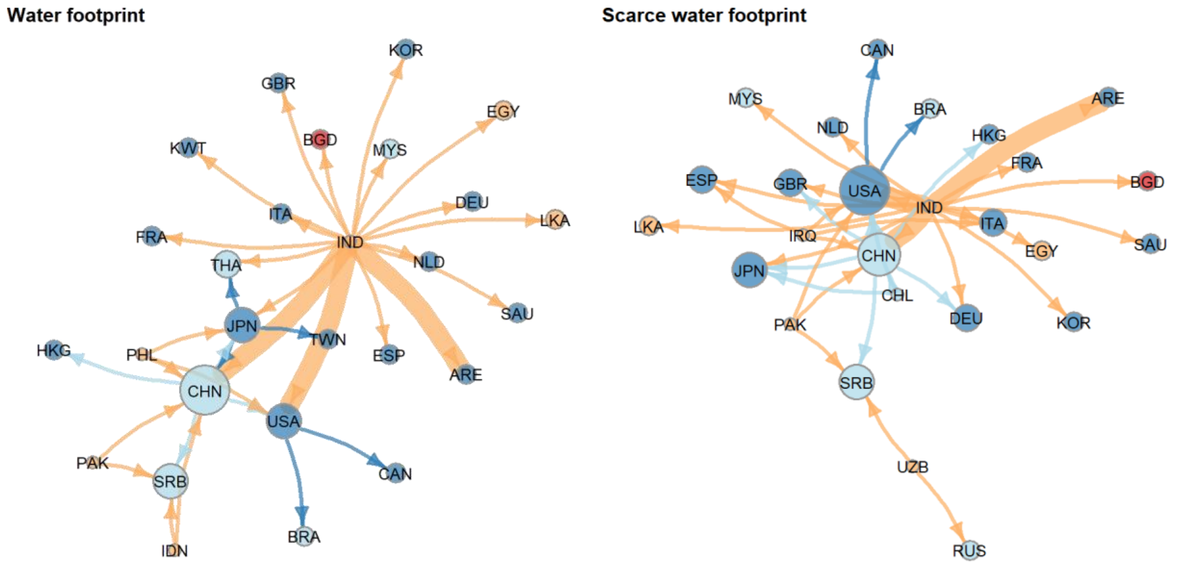


SO2 footprint



Student flows





Supplementary Fig. 2. Map of income group.